The Defense Science Board
2001 Summer Study

on

DEFENSE SCIENCE AND TECHNOLOGY

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OFFICE OF THE SECRETARY OF DEFENSE
3140 DEFENSE PENTAGON
WASHINGTON, DC 20301-3140

DEFENSE SCIENCE
BOARD

JUN 14 2002

MEMORANDUM FOR PRINCIPAL DEPUTY UNDER SECRETARY OF DEFENSE (ACQUISITION, TECHNOLOGY & LOGISTICS)

SUBJECT: Final Report of the Defense Science Board (DSB) Summer Study Task Force on Defense Science and Technology

I am pleased to forward the final report of the DSB Task Force on Defense Science and Technology. The Task Force was tasked to address issues involved in assuring that the U.S. continues to gain access to and develop technology from which to gain military advantage. The Task Force looked at future technologies that should be developed and exploited for military application, with particular emphasis on those potential technologies that can provide the U.S. military an asymmetric advantage.

The Report makes substantive recommendations on the content and conduct of the DoD science and technology program. In their report, the Task Force states that the Department of Defense must be enabled by transformation of its science and technology enterprise and must continue to adapt rapidly to meet challenges and exploit opportunities.

I endorse all of the Task Force's recommendations and propose you review the Task Force Co-Chair's letter and report.

William Schneider, Jr.

William Schneider, Jr.
DSB Chairman

OFFICE OF THE SECRETARY OF DEFENSE
3140 DEFENSE PENTAGON
WASHINGTON, DC 20301-3140

DEFENSE SCIENCE BOARD

MEMORANDUM FOR THE CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Final Report of the Defense Science Board Summer Study on Defense Science and Technology

Transformation of the Department of Defense must be enabled by a transformation of its science and technology enterprise, which is a critical enabler for superior warfare capabilities. Today's national security environment is characterized by uncertainty and by a rapid pace of change. The DoD science and technology program needs to continue to adapt rapidly to meet challenges and exploit opportunities that arise in this environment.

The summer study task force was asked to review and evaluate three areas: (1) how the Department's S&T investment should be spent; (2) the level of investment that should be made in science and technology; and (3) how the military can realize the most value from this investment. In addition, the task force was asked to examine the contribution of the DoD laboratories in this changing world.

The task force believes that significant changes are needed in both the content and conduct of the DoD science and technology program if the Department is to continue to sustain a decisive military advantage into the future.

Our recommendations focus on transforming the Department's S&T enterprise. They fall in seven areas:

1. **Invest in new S&T initiatives in support of four transformational challenges:** defending against biological warfare defense, finding difficult targets, making timely and accurate decisions, and enabling high-risk operations. Expand and provide more focused management for ongoing related S&T programs.
2. **Maintain the level of S&T investment** at 3 percent of the overall DoD budget as currently planned by the Department. Provide additional funds for new S&T priorities by reprioritizing current programs.
3. **Exploit commercial technology** through expanded use of commercial products and processes; elimination of barriers for commercial firms to do business with the DoD; and new initiatives to forge relationships with commercial industry.

4. **Foster operational experimentation** as an integral element of a new S&T enterprise through assigned experimental units and sustained senior attention.

5. **Establish a new technology transition process** with wide use of spiral development, routine inclusion of independent red teams, and acceleration of the acquisition cycle. Vest responsibility for joint operational experimentation, ACTDs, and transition with the Director of Transformation.

6. **Enable development and acquisition of joint R&D** by establishing points of clear responsibility in joint C4ISR and biological warfare defense.

7. **Restructure the DoD laboratories and rebuild the scientific and engineering workforce** based on a major review of the function and workforce in each laboratory.

Implementation of this set of recommendations will provide an enormous improvement in the focus and effectiveness of the defense S&T enterprise. We believe that we have identified those changes that will offer the greatest beneficial results today.

Only modest funding is required to fully implement all of the recommendations made in this report. The Department should be able to expand existing programs and conduct new S&T initiatives to support transformational challenges without new funding by reprioritizing within the S&T program. Funding for operational experimentation and technology transition should grow over the span of several years.

This study was completed prior to the events of September 11, 2001 and those happenings are therefore not reflected in the text. However, a review of the recommendations in light of that event confirms the validity of the conclusions and the need to accelerate implementation.

Anita Jones, Co-chair

Larry Lynn, Co-chair

TABLE OF CONTENTS

PREFACE

The Department of Defense is fundamentally transforming its strategy, policies, and forces. This transformation is motivated by a vastly different security environment that has emerged over the last decade. Where once a single monolithic threat—the Soviet Union—dominated the nation's security planning and programming, today's environment comprises a broader, more diffuse set of concerns: terrorism, biological warfare, regional tensions, and an array of other transnational challenges. It is an environment characterized by uncertainty, but more importantly by a rapid pace of change.

Transformation of the Department of Defense must be enabled by a transformation of its science and technology enterprise, which is so critical to its superior warfare capabilities. If the Department fails to adapt to the pace of technological change, fails to rapidly integrate new and breakthrough technologies into its operational systems, or fails to sustain a research and development environment that fosters innovation, the United States stands in danger of losing what today is a significant lead in military capability.

Assuring that the United States continues to gain access to and develop technology from which to gain military advantage is the subject of this report.

EXECUTIVE SUMMARY

Technology has been and must continue to be a key enabler of military advantage, both in conflict and in situations where conflict is close at hand. Over the years, the Department of Defense (DoD) science and technology (S&T) program has discovered, invented, harnessed, and demonstrated such enabling technologies. As industry becomes more global, as scientific endeavors in other countries become more competitive, and as affordable technology increasingly issues from commercial sources, the DoD science and technology program needs to continue to adapt to meet challenges and exploit opportunities that arise.

The Defense Science Board 2001 Summer Study task force was asked to examine three aspects of the DoD science and technology program:

- How the Department's S&T investment should be spent.
- The level of investment in science and technology.
- How the military can realize the most value from this investment.

The task force concluded that significant changes are needed in both the content and conduct of the DoD science and technology program if the Department is to continue to sustain a decisive military advantage.

The task force offers recommendations for change in the following areas:

- New initiatives and focus for sustained S&T efforts.
- The level of S&T investment.
- Adaptation of commercial technology.
- Operational experimentation.
- The technology transition process.
- Research and development for joint requirements.
- DoD laboratories.

S&T INVESTMENT PRIORITIES: TRANSFORMATIONAL CHALLENGES

Challenges in the national security environment mean changes for the Department's science and technology program. New threats, new adversaries, emerging disruptive technologies, and the speed with which knowledge spreads and technology is applied are among the new challenges to which the Department of Defense must respond.

The S&T enterprise must support these needs. The task force has identified four S&T transformational challenges that will provide real military potential if given more focus and acceleration. In each case, the task force identified an ongoing S&T effort that warrants significant augmentation, acceleration, and increased focus. It also identified a particularly high-payoff and timely new project that can help focus the efforts in each area. In addition to implementing these focused programs, the task force recommends that the Department continue its level of effort in basic research in emerging areas such as nanotechnology and quantum science.

S&T CHALLENGE #1: DEFENDING AGAINST BIOLOGICAL WARFARE

Biological agents present an increasing threat to the U.S. military, allies, and homeland. The only effective strategy against this threat is to address all dimensions of defense, from deterrence to therapeutics. A DoD-wide strategy for biological warfare (BW) defense needs to be implemented and supported by a comprehensive science and technology program. DoD is investing in S&T research in a number of areas, but the current program is not coordinated in a way that will provide effective, integrated results. Moreover the current program needs a major infusion of resources: an increase from the current $250 million to at least $1 billion per year.

The high-payoff, focused project recommended for the biological warfare defense area is "Pathogen to Hit." Its aim is to develop an effective therapeutic response to biological agents by dramatically compressing the time it takes to identify and develop effective drugs. Modern geonomics and proteomics provide new tools to make this goal achievable. While this is but one step in an integrated solution, an effective therapeutic response can be a powerful deterrent against the use of biological warfare agents.

S&T CHALLENGE #2: FINDING DIFFICULT TARGETS

Recent operational experiences indicate a need to improve the military's ability to find targets that are concealed by camouflage, foliage, or structure, or that are underground; to identify moving targets, especially in adverse weather; and to discriminate decoys from real targets. The United States needs a fully-integrated, layered intelligence, surveillance, and reconnaissance (ISR) capability. The task force believes that with a more focused effort over the next decade, progress in developing such a system is possible. S&T efforts will need to focus on developing new capabilities in remote sensing and data processing.

The focused project recommended in this area is referred to as "Micro-Sensor Networks." Proliferated surface sensors can provide another tier of a layered defense, complementing airborne sensors and unmanned aerial vehicles with sensors that operate "underneath" concealment. Technological developments in micro-sensors—making them more capable, smaller, diverse, and lower in cost—as well as advances in adaptive networks provide an opportunity to develop the surface-based sensing tier.

S&T CHALLENGE #3: MAKING TIMELY, ACCURATE DECISIONS

Today military planning takes a long time, which may result in plans that do not reflect reality at the time a mission is executed. The task force believes that a focused, expanded S&T program can result in a much more effective, integrated, automated decision support system, capable of being used to synchronize both individuals and groups in joint and combined operations. Such a system would include automated decision support services as well as self-configuring, self-healing mobile networks.

Better decisions can also be enabled by increasing leadership experiences and by a more diverse set of operational tactics and doctrine. Because of its powerful potential, the recommended focused project to address this challenge is the exploration of "Massive Multi-Player Gaming." This new cultural and technical phenomenon offers the potential for a new way to devise and to explore military concepts. The virtual environment provides a platform in which many individuals can participate regardless of location, an opportunity for free-form experimentation, and the potential for faster, more innovative concept development.

S&T Challenge #4: Enabling High-Risk Operations

The majority of military casualties occur in close combat. Unmanned systems offer the potential to effectively engage the adversary while lessening friendly losses. Advances have been made in software agents and robotic control technology that can accelerate the development of unmanned systems. The task force advocates an expansion of existing S&T programs in unmanned systems that focus on operational demonstrations designed to achieve specific missions such as an urban assault in a free-fire zone.

Combat performance is also limited by the human element. The potential for improving “human performance” is sufficiently exciting that a program of research and development should be undertaken in that area. Demands on the warfighter are growing as operational tempo and the sophistication of weapon systems increases. Improving human performance—using a myriad of techniques that could increase strength, memory, or sensory perception or decrease requirements for sleep and food—is one way to advance warfighting capabilities.

S&T INVESTMENT STRATEGY

The task force believes the four transformational challenges described above are appropriate investment priorities for the Department.

The figure below summarizes the estimated level of current investment as well as the recommended new investment in each of the areas discussed. In the aggregate, research in the areas of the four transformational challenges and in the areas recommended by the task force for long-term basic research, currently receive funding of about $1.7 billion per year. The task force recommends increasing this investment by $1.8 billion, to approximately double the annual funding for these programs and thus make possible the changes and initiatives recommended by the task force. Funding for these initiatives should come from reprioritizing existing S&T programs (15-20 percent of the current S&T funding), although other sources are also appropriate, such as changes in accounting for advanced concept technology demonstrations (ACTDs).

Current Funding (est)
~$1.7B

Increased Funding
~$1.8B

Transformational Challenges

	Defending Against Biological Warfare	*Finding Difficult Targets*	*Making Timely, Accurate Decisions*	*Enabling High-Risk Operations*
Focused Ongoing S&T Programs	**BW Defense S&T** *$250*+**$750M**	**ISR S&T (sensors, exploitation)** *$650*+**$200M**	**Decision Tools Network S&T** *$250*+**$150M**	**Unmanned Systems** *$50*+**$150M**
New S&T Projects	**Pathogen to "Hit"** *$0* +**$200M**	**Micro-Sensor Networks** *$50* +**$100M**	**Massive Multi-player Gaming** *$0* +**$20M**	**Human Performance** *$150* +**$30M**

Long Term Research	**Nano-technology**	*$150* +**$100M**	**Quantum**	*$100* +**$75M**

Each of the S&T programs discussed (listed in the top row of the figure) should be managed by a single organization but executed by those best qualified—which typically will include many organizations. The task force recommends that the Defense Threat Reduction Agency (DTRA) be given the responsibility for biological warfare defense S&T and that the other programs in the upper row be managed by the Director, Defense Research and Engineering (DDR&E) but with more control than is common today. The focused, high-payoff projects in the second row are particularly well suited to the Defense Advanced Research Project Agency (DARPA) style of project-oriented management. Research can be managed loosely, as is the current practice today.

S&T Investment: Recommendation #1

The additional resources needed to fund the four S&T initiatives described should eventually reach a total of about $1.8 billion annually. These initiatives can be funded through three measures.

The Secretary of Defense should

- ***Achieve and sustain investment in S&T of 3 percent (of the top line DoD budget.***

The Under Secretary of Defense for Acquisition, Technology and Logistics (USD (AT&L)) should

- ***Reprioritize 15-20 percent of the current S&T budget over the next two to three years.***
- ***Provide $500 million of 6.4A funds to move current ACTDs from 6.3 and use current 6.3 funds as part of funding new initiatives.***

MANAGING S&T INITIATIVES: RECOMMENDATION #2

Managing the recommended S&T initiatives should take different form for different projects—options include direction under a single focal point, management within DDR&E, a project-oriented approach like that of DARPA, and coordination as scattered efforts.

The USD (AT&L) should

- ***Establish a single focal point for biological warfare defense S&T.***
- ***Re-institute the 'Format-I' to provide muscle for the DDR&E to effectively control focused ongoing S&T programs.***

PROCESS IMPROVEMENTS IN THE S&T ENTERPRISE

There is an imperative related to each of the transformational challenges: the need to capture and exploit technological advances that are progressing largely in the commercial world—and that are progressing at great speed. The Department's science and technology enterprise must become more agile, more flexible, and more adaptive to be effective in this challenging environment. In particular, as technology becomes more rapidly available to potential adversaries, DoD must be able to incorporate the latest technology into military capabilities more rapidly as well—in timeframes measured in months, not decades.

Over the last ten years, the Defense Science Board alone has conducted nearly three-dozen studies on improving processes in the S&T enterprise. Drawn from this body of work, ***this task force has identified two areas that have the potential to transform the entire S&T, acquisition, and requirements process***. They are as follows:

- Assuring access to ***developing commercial technology***.
- Adopting an ***integrated process*** of operational experimentation, spiral development, and technology transition to users.

In addition, the task force believes it is important to comment on and make suggestions regarding one long-standing and much-studied problem: ***rejuvenation of the DoD laboratories***.

ACCESS TO COMMERCIAL TECHNOLOGY: RECOMMENDATION #3

The Department of Defense no longer leads in the development of many technologies essential in enabling the nation's future military superiority. Because of its complex and burdensome system of procurement regulations and processes—such as accounting and information system requirements—the Department continues to deny itself access to many industries.

To improve access to commercial industry and ensure continued exploitation of commercially developed technology, the Department must pursue a three-prong approach: 1) provide incentives within DoD to use commercial products, practices, and processes as the norm; 2) reduce barriers that inhibit commercial firms from working with DoD contractors and with DoD directly; and 3) foster "relationships" and create new incentives with critical technology sectors to motivate them to apply their knowledge and people to critical national security challenges.

The USD (AT&L) should

- ***Mandate the use of commercial practices, tools, techniques, components, software, and materials in DoD systems by establishing commercial technology as the norm; require justification for DoD-specific technology.***
- ***Develop and implement acquisition processes that remove barriers and create incentives for commercial corporations to support DoD.***

The Secretary of Defense should

- ***Personally engage with the biotechnology and pharmaceutical industries to build relationships with DoD and create effective partnerships.***

- ***Forge close relationship with the Secretary of Health and Human Services.***

OPERATIONAL EXPERIMENTATION: RECOMMENDATION #4

The Department of Defense must dramatically improve its S&T and acquisition processes or risk being out-paced by its adversaries. In particular, there is a need for more rapid transition from technology to system within timeframes that are measured in weeks or months. Operational experimentation and spiral development, properly executed, force a more integrated approach and provide the basis for an improved technology transition process.

Operational experimentation addresses all three elements of the Department's transformation process—changes in organization of forces, changes in doctrine and tactics, and changes in technology. The value of experimentation is to pursue many options and ideas and to provide a forum for collaboration between the operational warfighter and technologist.

The Chairman, Joint Chiefs of Staff should

- ***Form experimental units in each Service and Joint Forces Command.***
- ***Form corresponding, dedicated operational red teams.***
- ***Assign senior points of responsibility for fostering operational innovation and full use of experimentation.***

The USD (AT&L) should

- ***Provide funds for Joint and multi-Service experimentation.***
- ***Fund and support increased use of ACTDs. Decrease timescales and formality.***

A NEW TECHNOLOGY TRANSITION PROCESS: RECOMMENDATION #5

The science and technology and acquisition processes need to be considered as a single enterprise. Within this enterprise, the purpose of the S&T community is to generate options and opportunities for the warfighter. Significant changes are needed to more closely integrate operational experimentation, spiral development, and technology

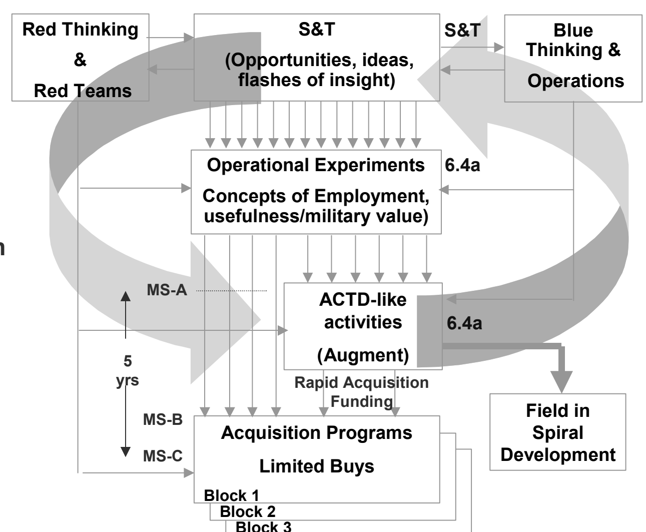
transition—providing a path from the S&T base to the user. Key elements of a new approach include a dramatically shorter acquisition cycle, expanded use of red teaming, expanded use of ACTDs, spiral development, and operational experimentation.

The USD (AT&L) should

- ***Implement the new process outlined for innovative concept development and expanded use of red teams and ACTDs.***
  - Mandate 5-year acquisition cycle.
- ***Give the Director of Transformation responsibility for joint operational experimentation, ACTDs, and technology transition.***
- ***Provide 6.4A funds to catalyze change.***
  - New funds growing to ~1.4 billion per year.
  - Approximately $650 million of this funding should be under direct control of the Director of Transformation; the balance should be in ACTDs under Services.

What's New

- **S&T driven by 5-year acquisition cycle**
- **Pulls S&T**
- **Dynamic & iterative**
- **Red teaming & action**
- **Rapid spiral development**
- **More experiments bringing players together**
- **Expanded ACTDs as the S&T customer**
- **Rapid acquisition funds**



RESPONSIBILITY FOR JOINT RESEARCH AND DEVELOPMENT: RECOMMENDATION #6

There is a special case in the technology transition area that requires further action: the lack of a joint development organization for critical *joint* warfighting capabilities. Without a joint development organization, there is no customer pull and there is no integrated approach to systems or solutions. Three areas where the problem has become acute are joint command and control; joint intelligence, surveillance, and reconnaissance; and biological warfare defense.

The Secretary of Defense should

- ***Establish organizations and activities responsible for joint research, development and acquisition in command, control, communications, and computers and intelligence, surveillance, and reconnaissance (C4ISR).***
  - Joint Forces Command and a Joint Program Office (co-located)
  - Adequate technical and acquisition support
- ***Establish single point responsibility for biological warfare defense research, development and acquisition at DTRA.***

REJUVENATING THE DOD LABORATORIES: RECOMMENDATION #7

Numerous studies have looked at the DoD laboratory system, identifying serious problems. However, few have focused on the diverse nature of laboratory functions as a basis for rejuvenating the laboratory system. Much of the activity conducted in the laboratories, and the majority of funds expended in or flowing through the laboratories, are not related to S&T. The laboratories are involved in engineering development, testing, in-service support and engineering, and acquisition support. With a better understanding of the activities, functions, and workforce of each laboratory, it should be possible to significantly reshape the laboratory structure.

The USD (AT&L), with direction of the Secretary of Defense, should instruct the DDR&E to

- ***Review each laboratory in detail and determine individual courses of action, to include the following:***

  - Administrative personnel transfers.
  - University management.
  - Privatization, consolidation, or closure.
- ***Complete review and begin taking action within 9 months with end goal of 2005.***
- ***In any case, especially for those likely to remain structured as they are, implement recommendations of the most recent Defense Science Board study, Efficient Utilization of Defense Laboratories (October 2000).***
  - Focus on personnel and quality improvements.

IN CONCLUSION

Two challenges will fundamentally change the nature of the S&T enterprise and military capability:

- Rapid technology transition—time matters.
- Transformation to new ways of fighting.

Technology is one enabler of new military capabilities and is typically most effective only in the context of new concepts of operations and doctrine. To accomplish both rapid technology transition and transformation to new ways of fighting, the Department must change its S&T enterprise through operational experimentation, rapid spiral development, and evolutionary acquisition. Only then will the Department be able to fully realize the benefits of the S&T investments described in this report.

CHAPTER I

OVERVIEW AND RECOMMENDATIONS

Over the years, the DoD science and technology (S&T) program has discovered, invented, harnessed, and demonstrated technologies that have become key enablers of military advantage. However, the technology landscape has undergone many changes in recent years—industry has become more global, scientific endeavors in other countries have become more competitive, and affordable technology increasingly issues from commercial sources. As a result, the DoD science and technology program needs to continue to adapt to this evolving landscape to meet challenges and exploit opportunities that arise.

Significant changes are needed in both the content and conduct of the DoD science and technology program if the Department is to continue to sustain a decisive military advantage. This report makes recommendations in the following areas:

- New initiatives and sustained S&T efforts.
- The level of S&T investment.
- Adaptation of commercial technology.
- Operational experimentation.
- The technology transition process.
- Research and development for joint requirements.
- DoD laboratories.

This introductory chapter discusses each of these issues and states the task force recommendations. The recommendations are discussed in further detail in the chapters that follow.

SCOPE AND STUDY APPROACH

The Defense Science Board 2001 Summer Study task force was asked to examine three areas:[1]

- ***How the Department's S&T investment should be spent***. What future technologies should be developed and exploited for military application? Characterize essential attributes of the Department's S&T investment.

[1] The complete terms of reference for the *Defense Science Board Summer Study on Defense Science and Technology* can be found in Annex A. Annex B lists the members of the summer study task force.

- ***The level of investment in science and technology***. How much of the Department's budget should be invested in science and technology endeavors, today and in the future?
- ***How the military can realize the most value from this investment***. What changes can be made in the way the Department manages and executes its S&T program to improve the return on its S&T investment?

STUDY APPROACH

Changes in the national security environment mean changes for the science and technology program. To be successful, the Department's S&T program must address:

- New threats and multiple adversaries.
- Emerging disruptive technologies that are driven commercially and globally, not by DoD.[2]
- Increased speed with which knowledge spreads and technology is applied.
- Asymmetric costs of some weapon exchanges.

To assess the success with which the Department's S&T enterprise is responding to these challenges, the task force pursued two separate but necessarily related paths, as Figure 1-1 depicts: it examined the need for new military capabilities and technological opportunities.[3]

At the intersection of these two paths, the task force identified a set of key transformational challenges for the DoD. Each of these challenges is sufficiently important that it deserves a well-focused, aggressive effort to bring the military capability to the warfighter.

For each of the four challenges, the task force examined supporting science and technology programs and made recommendations. In some cases the task force recommends augmentation of and/or better focus for ongoing programs. Specific new initiatives were identified as pacesetters within the focused programs. In addition, the task force examined the Department's investment in basic research.

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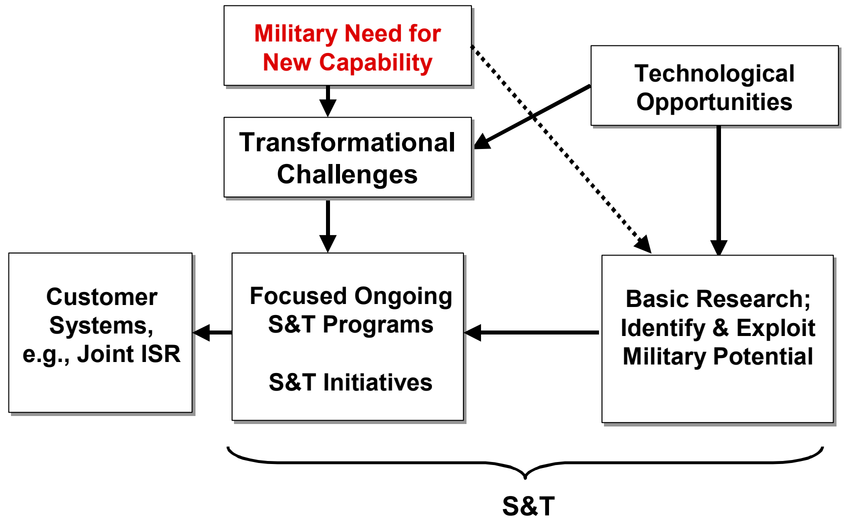
2 Disruptive technologies are those technologies that tend to change processes or approaches to capability as opposed to bettering existing processes or approaches in an evolutionary way.

3 A separate panel of the Summer Study task force addressed each of these paths. The Military Applications panel examined military capabilities; Chapter II contains the findings of their effort. Chapter III presents the work of the Technology panel, which focused its efforts on exploring technological opportunities.

Figure 1-1. Study Approach



Finally, the task force examined the institutions and processes that underpin or interface with the S&T enterprise.[4] There have been many studies and recommendations in these areas over the past decade which have recognized serious problems. Rather than review or repeat the prior recommendations, this study tried to identify and concentrate on a small number of improvements that would yield the greatest impact. The two areas believed to have the potential to transform the science and technology process were:

- Assuring access to developing commercial technology.
- Adoption of an integrated process of operational experimentation, spiral development and transition of technology to the users.

In addition, it became clear, as a result of this assessment, that there is a lack of a "customer" for S&T in some critical areas, particularly joint command and control; joint intelligence, surveillance, and reconnaissance (ISR); and biological warfare (BW) defense. As a result, there is an absence of customer "pull" for new technology in these areas. That in turn impedes both the supporting S&T program execution and the speed of technology transition.

4 A third panel, Investment Strategies, examined the policies and processes that drive the S&T enterprise. Their work is reported in Chapter IV.

TRANSFORMATIONAL CHALLENGES: S&T INVESTMENT PRIORITIES

In deriving S&T investment priorities, the task force sought answers to some fundamental questions from a broad audience in the national security community. It sought to understand:

- What most worries current Combatant Commanders?
- What must the Services do well operationally?
- Where are the consequences of operational failure unacceptable?
- What is necessary to enable future operational concepts?
- What dangers do threats pose for operational capabilities?
- What technological advancement will strongly influence global military capabilities?
- How will current and emerging technologies actually affect warfare?

The responses to these questions were instructive, and discussion with the Commandant Commanders was particularly illuminating. These inputs helped the task force derive nine high-priority military needs: (1) biological weapon defense, (2) location of difficult targets, (3) timely and accurate decision making, (4) enablers of high-risk operations, (5) missile defense, (6) affordable, precision munitions, (7) enhanced human performance, (8) rapid deployment and employment, and (9) global effects. Each of these needs is critical and recommendations for related science and technology and acquisition programs for each one are discussed in detail in Chapter II.

These military needs were then subjected to further tests to determine which should be the highest priorities for defense S&T. This additional filtering considered the following:

- ***Are these vital military capabilities?*** The task force determined that all of them are.
- ***Is there a technological opportunity to advance that would deliver enduring advantage, for a decade or more?*** In some areas, such as global effects, a substantive technology enabler was not yet evident.
- ***Finally, is there a need for more focus or acceleration in the S&T program?*** The task force found that ongoing

programs already provide emphasis in a number of areas including missile defense, Future Combat System, rapid decisive operations, affordable munitions, space, and high-energy weapons.

In the end, four transformational challenges, shown in Figure 1-2, emerged from this filter. These four challenges will provide real military potential if given more focus and acceleration:

- Defending against biological warfare.
- Finding difficult targets.
- Making timely, accurate decisions.
- Enabling high-risk operations.

Figure 1-2. Four Transformational Challenges

Transformational Challenges

	Defending Against Biological Warfare	*Finding Difficult Targets*	*Making Timely, Accurate Decisions*	*Enabling High-Risk Operations*
Focused Ongoing S&T Programs	**BW Defense S&T**	**ISR S&T (sensors, exploitation)**	**Decision Tools; Network S&T**	**Unmanned Systems**
New S&T Projects	**Pathogen to "Hit"**	**Micro-Sensor Networks**	**Massive Multi-Player Gaming**	**Human Performance**
Long Term Research	**Nano-technology**		**Quantum**	

These four transformational challenges are discussed below. For each one, the task force identified an ongoing S&T effort that warrants significant augmentation, acceleration, and increased focus. It also identified a particularly high-payoff and timely new project within each.

In addition to these focused programs, the task force found that the Department should continue its level of effort in basic research. This program is particularly crucial to avoiding technological surprise. Nanotechnology and quantum science are examples of such research. These are areas that could, as technology matures, either provide exceptional new capabilities or, if in the hands of adversaries, deny important capabilities to the United States.

CHALLENGE #1: DEFENDING AGAINST BIOLOGICAL WARFARE

Biological agents present a new threat to the U.S. military, allies, and homeland. The only effective strategy against this threat is to broadly address all dimensions of defense from deterrence to therapeutics. The topic of biological warfare defense has been addressed in three recent Defense Science Board (DSB) studies, which concluded that:[5]

> *The present U.S. defense effort ... will not effectively counter the current threat.*
>
> *This effort is hampered by an absence of a vision of what is required and lacks leadership and coherent organization.*

The task force believes that it is critical to develop a DoD-wide strategy for biological defense—a recommendation made by all three recent DSB studies. That strategy still needs to be implemented. ***A DoD-wide strategy should be supported by a comprehensive science and technology program for BW defense***. An S&T program should address all facets of biological warfare defense: warning, detection and characterization, passive protection, intelligence, incident response, forensics, collective protection and decontamination, diagnostics, and vaccines and therapeutics. Each of these areas needs serious and focused

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[5] *The Defense Science Board 1999 Summer Study Task Force on 21st Century Defense Technology Strategies, Volume I* (Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics), 1999;*Protecting the Homeland*, *Report of the Defense Science Board Task Force on Defense Against Biological Weapons—Leveraging Advances in Biotechnology and Medical Informatics to Improve Homeland Biodefense Capabilities*, 2000 Summer Study, Volume IV; and *Report of the Defense Science Board/Threat Reduction Advisory Committee Task Force on Biological Defense,* (Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics), June 2001.

S&T research. Even partial or incremental S&T results would collectively enable an improved defense posture.

The Department is addressing a number of these areas, but the current program is not coordinated in a way that will provide an effective, integrated defense. ***Moreover, the current program needs an infusion of resources: an increase from the current $250 million to at least $1 billion per year.*** Additional resources are likely to be required in the longer term. With an aggressive effort, the Department can be successful in addressing the challenge of biological defense.

Pathogen to "Hit"

Biological agents are terror weapons in part because the nation lacks effective therapeutic responses. Today, it takes roughly 10 to 15 years to develop a safe drug for a specific purpose.

The task force believes that it is possible for the United States to develop a therapeutic response for bioagents. The process of finding an effective drug to halt the damaging process that ensues when a pathogen enters the body has two steps. The first step is moving from a pathogen to a "hit." The "hit" is a candidate drug that will intervene in the damaging process that the pathogen triggers. There are two parts to finding a hit: (1) analysis of the pathogen identifies (multiple) targets of intervention which if successful will halt the destructive process; and (2) drug candidate generation which produces candidate drugs that are optimized for their effectiveness in making the desired intervention in the human body.

Modern genomics and proteomics provide new tools: rapid and high-throughput empirical laboratory processes and computationally based drug design. When it can be used, computational analysis is much faster than laboratory experimentation. In either case, specific knowledge at the molecular level leads to drugs that are more specific, and thus make possible the desired intervention with fewer negative side effects or consequences.

The second step in the process is to perform toxicity and safety screening. The pathogen to hit process took five to six years a decade ago, but now occurs in about half that time or less. In limited cases, modern advances have created reasonable drug candidates in as little as nine months. It appears that the same tools that can reduce the pathogen to hit duration will be useful in shortening the toxicity and safety screening process. Further, increased quality of hits can be expected to lead to better performance in later screens.

The pharmaceutical industry drives this research. However, there is a role for DoD that is not being addressed by others. Reference databases for bioagent threats are needed to perform the computational pathogen to hit step, and DoD can play a role in building these databases. The Department should also leverage its computational expertise to accelerate first-principles approaches and build a research and development (R&D) bridge to the pharmaceutical industry, academia, and government agencies.

The task force recommends the Department undertake an initiative that focuses on further compressing the pathogen-to-hit process, funded at $200 million per year for five years. In the near term, the initiative would seek to compress the pathogen to hit process from years to months, in the mid-term from months to weeks, and in the longer run to compress the toxicity and safety screening processes by a comparable amount. A collateral benefit of this research would be to lower the cost of developing drugs that are relevant to the military, but that the drug industry is not motivated to pursue. ***While it is but one of the steps required in developing an integrated biological warfare defense, possession of a process that can quickly develop an effective therapeutic response to pathogens would itself be a deterrent against the use of biological warfare agents.***

CHALLENGE #2: FINDING DIFFICULT TARGETS

Recent operational experiences indicate a need to improve the military's ability to find targets that are concealed by camouflage, foliage, or structure, or that are underground; to identify moving targets, especially in adverse weather; and to discriminate decoys from real targets. In the Persian Gulf, for example, approximately 6,000 allied sorties were flown against SCUD TELs, but none were actually found. In Kosovo, many tank "kills" were strikes on decoys.

There are a variety of airborne sensors in existence with a range of capabilities for remote sensing. The data from these sensors must be brought together, correlated, and assessed to translate the data into information. New capabilities to process enormous volumes of data are thus required, as well as some limited creation of additional sensor capabilities. The extensive use of unmanned aerial vehicles (UAVs)—from large, high-altitude platforms to micro-air-vehicles—can enhance remote detection.

The United States needs a fully integrated, layered intelligence, surveillance, and reconnaissance capability. The task force believes that with a more focused effort over the next decade progress in developing such a system is possible. Funding should be increased by an additional $200 million per year.

Microsensor Networks

Proliferated surface sensors can provide another tier of a layered defense, complementing airborne sensors and UAVs. Technological developments in microsensors—making them more capable, smaller, more diverse, and lower in cost—as well as advances in adaptive networks provide an opportunity to develop the surface-sensing tier. These microsensors would be dispensed in great numbers in targeted areas, based on cueing from longer-range assets. Local ground nodes with higher power would interrogate the microsensors, use the Global Positioning System (GPS) to locate them, and would communicate information back to an airborne communication vehicle. These sensors would essentially look up and around, and would have the potential to observe hidden targets in close proximity.

The goal of a microsensor S&T program, with funding increasing to $100 million per year, is to affordably increase the probability of detection and correct identification of increasingly difficult targets—those that are movable, under foliage, in buildings, or underground. The key to finding and identifying difficult targets is integrated operations among all surveillance layers. The microsensors are one very important component of that overall operational concept; they must be both effective and individually inexpensive since proliferation in very large quantities (such as tens of thousands) will be the key to their contribution.

CHALLENGE #3: MAKING TIMELY, ACCURATE DECISIONS

Today, military planning takes a long time. As a result, planning occurs well before a mission and may result in stale plans that do not reflect reality at the time of execution. Planning time needs to be reduced from days to hours, so that operations can be executed at a speed determined by the commander, not the supporting information system. A commander must be able to “turn within the decision time frame of an adversary.” ***The task force believes that a more focused, expanded program can result in a much more effective integrated, automated***

decision support system, capable of being used to synchronize both individuals and groups in joint and combined operations.

The development of an integrated, automated decision support system should be driven by demonstrations of its various elements, which will include automated decision support services as well as self-configuring, self-healing mobile networks. These component demonstrations should culminate in integrated technology demonstrations that focus on system survivability that is tolerant of degradation.

While the civilian sector leads in communications and network research, its network requirements differ from those of the military. In particular, much of the infrastructure of a civilian network is fixed; for the military, these networks must typically be mobile. Thus, the Department's research must focus on its unique requirements, while leveraging civilian R&D. Science and technology funding to support these needs should increase by $150 million per year.

Massive Multi-Player Gaming

A new cultural and technical phenomenon—massive multi-player virtual environments—offers the potential for a new way to devise and to explore military concepts. A virtual environment provides a platform in which many participants can participate regardless of location. In addition, it provides an environment that inexpensively supports free-form experimentation. Such experimentation fosters the generation of more options and may result in faster, or more innovative, concept development. In civilian games there is an observed phenomenon called emergent behavior—that is, groups of individuals self-synchronize and devise group strategies. As supported by information technology, massive multi-player gaming is a new medium in which to explore concept formation; the military should experiment with it.

An S&T initiative would leverage the civilian on-line entertainment industry, in which the most rapid growth is in massive multi-player games. The goal is to create a military toolkit with virtual environments that support the involvement of active military in the field. The program would support exploration in unrestricted play, identifying both creative concepts and individuals. The DoD S&T challenge is to understand, identify, and capture a useful record of emergent behavior in order to discover new concepts that emerge in an environment in which hierarchy does not dominate.

The task force advocates an experimental program in which the Joint Warfare Center or EUCOM Warrior Preparation Center acts as

the "concept-testing master" overseeing experimental use of the toolkit. To complement that activity, DARPA should explore innovative relationships with the gaming community and sponsor research on automatic detection and analysis of emergent behavior.

Within the first 18 months, the Department should experiment with off-the-shelf game engines supporting about 100,000 players. Over a five-year period, the program should build to a dedicated DoD concept exploration system potentially involving up to a million players in a variety of virtual environments.[6] The peacetime doctrine and concept development process is currently centralized, hierarchical, and time-insensitive. It involves very few individuals. Massive multi-player games offer an alternative that should be explored to determine whether it provides value.

CHALLENGE #4: ENABLING HIGH-RISK OPERATIONS

The fourth transformational challenge is to enable high-risk operations. The highest number of military casualties occurs in close combat; 85 percent of U.S. casualties occur within infantry. Unmanned systems offer the potential to effectively engage the adversary while lessening friendly losses. Advances have been made in software agents and robotic control technology, which can accelerate the development of unmanned systems. ***The task force advocates a focused expansion of existing S&T programs in unmanned systems, driven by demonstrations that have specific operational goals.***

The task force recommends two demonstrations. By 2006, there should be a platoon-sized demonstration of an urban assault in a free-fire zone. This demonstration would achieve an integration of combat effects through a mix of manned and semi-autonomous systems. The second demonstration, in the 2010 timeframe, would expand to a company-sized, autonomous search and clearance of urban buildings. In this case, unmanned systems would be expected to operate in a more challenging environment where mission duration and mobility would be consistent with operational tempo.

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6 Potential players include active, reserve, and National Guard forces; development organizations; industry; academia; and the test and evaluation community.

Human Performance

Demands on the warfighter are growing as forces operate with an increased operational tempo, using increasingly sophisticated systems. Improving human performance is one way to advance warfighting capabilities. Medical science has myriad techniques to restore disabled functionality—techniques that can also be applied to enhance normal functionality. Examples include increasing strength, memory, or sensory perception; decreasing requirements for sleep and food; and altering perceptions of pain. New opportunities in cognitive psychology, cell signaling and regulation, advanced therapies, sensors, implants, artificial organs, and drugs can be tapped.

For example, profiling—long used for pilots and special operations officers—can be extended to identify superior warfighters using genetic screening factors for cognitive abilities, reflexes, cardiac capability, and strength. Advances in medical technology could help with prevention, treatment, and care—boosting immunity, accelerating natural healing responses, or stabilizing injuries. Advances in understanding of endurance and physical performance can result in training benefits. ***Funding of $30 million per year is recommended to begin a program focusing on human performance with well-chosen, very specific goals.***

LONG-TERM RESEARCH

The science and technology program must include an element of long-term research in those areas that have the most potential for military application. It is critical that the DoD explore emerging technology, with a clear focus on potential future military capability. DoD-sponsored research in high-risk areas is also necessary to prevent technological surprise. The task force highlights just two key areas to illustrate research that might enable dramatically new military capability: nanotechnology and quantum information technology.

Nanotechology

It is now possible, in the laboratory, to design and manufacture at the atomic scale. For example, nanoscale electronics have been demonstrated that allow 16-bit molecular memory at 10 times the density of silicon CMOS. As nanotechnology matures, the potential for military application is great. It may be possible to design materials with the weight of plastic and strength of steel for ultra-lightweight combat vehicles. Pipes, hose and aircraft skin materials may be made ultra-durable and self-repairing.

The Department of Defense is already part of a multi-government agency initiative in this area, with a total investment that is in excess of a half a billion dollars per year and growing. DoD should focus on the fundamental research questions most related to the potential for new military capability and not likely to be adequately addressed with high priority elsewhere. Such questions include precise control of the size, separation, and placement of nanoscale components; connections between nano and macroscales for high-strength materials and electronics; fabrication of polymer nanocomposites; molecular recognition and signal transduction in nanoscale biomolecular systems; and deformation, fatigue and fracture of nanostructures. To address these questions, the task force believes that an additional investment of $100 million per year is warranted.

Quantum Information Technology

Control and detection of electron spin creates the potential for quantum computing and communication. Theory predicts that a quantum computer can factor large numbers quickly, and thus break today's encryption schemes. But it also offers the potential for unbreachable command and control, clock synchronization, and robust GPS. The theory for quantum computation is not yet well understood.

Quantum communication has been demonstrated in the laboratory and has potential for revolutionary capability. While practical realization of these capabilities is still a long way off, the United States cannot afford to have others get there first, and the United States does not currently lead in quantum research. DoD needs to invest sufficiently to stay in the game. The task force recommends that the Department increase its investment by $75 million per year.

S&T INVESTMENT STRATEGY

The task force believes that the four transformational challenges described above are appropriate investment priorities for the Department. The new initiatives identified, together with ongoing initiatives and others that will be developed, can offer a comprehensive program to address these challenges. Figure 1-3 summarizes the recommended investment in each of the areas discussed above and also shows an estimate of current

investment in that area. To be effective these programs need to be supported by increased investment and more focused management.

S&T Investment: Recommendation #1

The new resources required to fund the S&T initiatives recommended in the previous section—increases in ongoing S&T programs, new S&T projects, and long-term research—should eventually reach a total of about $1.8 billion annually. ***The task force believes that it is possible to fund these initiatives by reprioritizing 15 to 20 percent of the investments within the current $9 billion S&T budget over the next two to three years.***

Figure 1-3. S&T Investment

Current Funding (est) ~ $1.7B

Increased Funding ~$1.8B

Transformational Challenges

	Defending Against Biological Warfare	*Finding Difficult Targets*	*Making Timely, Accurate Decisions*	*Enabling High –Risk Operations*
Focused Ongoing S&T Programs	**BW Defense S&T** *$250*+$750M	**ISR S&T (sensors, exploitation)** *$650*+$200M	**Decision Tools Network S&T** *$250*+$150M	**Unmanned Systems** *$50*+$150M
New S&T Projects	**Pathogen to "Hit"** *$0* +$200M	**Micro-Sensor Networks** *$50* +$100M	**Massive Multi-Player Gaming** *$0* +$20M	**Human Performance** *$150* +$30M

Long Term Research	**Nano-technology**	*$150* +$100M	**Quantum**	*$100* +$75M

Reprioritizing the current program should be the primary path to funding S&T for the transformational challenges described in the previous section. Reprioritization would target funding cuts at programs with lower output potential, making it possible to increase investment in other areas without losing any significant output from the S&T system. Termination of programs or funding reductions should be considered when:

- Technology is clearly lagging behind that in the commercial world.
- DoD can rely on commercial technology and broadly understands it.
- Effort is sub-critical in size.
- Output is likely to have limited application.
- Unproductively redundant efforts are ongoing in multiple places.
- Successful conclusion will not make a material difference.
- DoD can otherwise anticipate low value in payoff.

In addition, the task force recommends that most of the funding for advanced concept technology demonstration (ACTDs), currently about $500 million/year, be funded from the 6.4 account but executed by S&T participants; this recommendation is consistent with the purposes and objectives of ACTDs.

Recommendation #1
S&T Investment

The Secretary of Defense should

- Achieve and sustain investment in S&T of 3% (of the top line DoD budget).

The Under Secretary of Defense for Acquisition, Technology & Logistics [USD (AT&L)] should

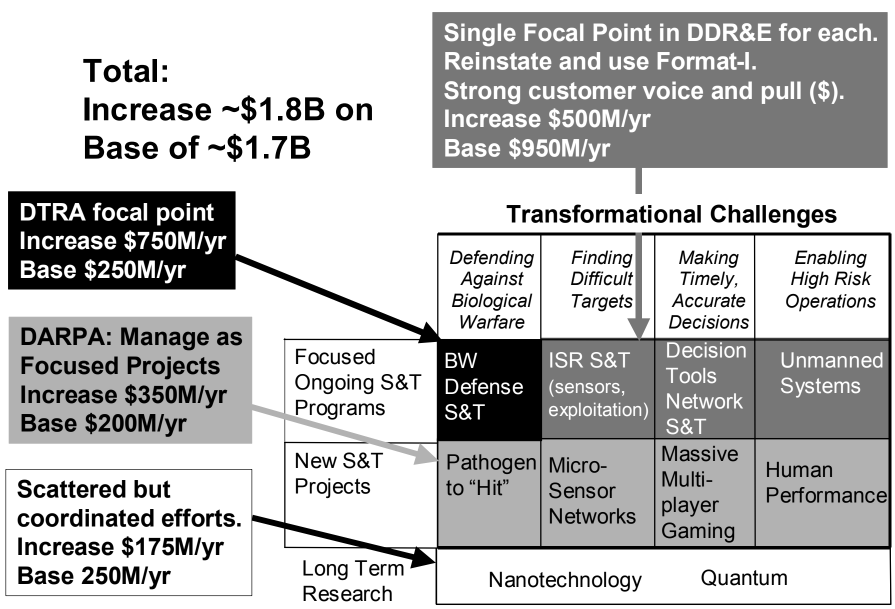
- Direct reprioritization of S&T to fully fund the S&T initiatives outlined, within the S&T budget.
  - Start now and complete within 9 months.
- Provide $500 million of 6.4A funds to move current ACTDs from 6.3 and use current 6.3 funds as part of funding of new initiatives.

MANAGING S&T INITIATIVES: RECOMMENDATION #2

Management of the recommended S&T initiatives should take different forms for different projects, as illustrated by the shaded gray areas in Figure 1-4.

The Defense Threat Reduction Agency (DTRA) should be assigned responsibility for managing a focused biological warfare defense program. The other ongoing S&T programs—ISR, decision tools and networks, and unmanned systems—need a focused management approach that draws together the spectrum of technologies being pursued in many organizations and provides coherence in their execution. A single focal point within the Director, Defense Research and Engineering (DDR&E) to manage each of these efforts is recommended.

Figure 1-4. Management Approach



It is essential that a program manager have true control of the funds in a given area, and that is not the case today within the Office of the Secretary of Defense. Twenty years ago, the DDR&E used an authority called "Format I" to exercise that control, but its use has since been discontinued. The Format I was essentially a notification to the

Comptroller that appropriated funds should not be released to a Service or agency until and unless the DDR&E approved the program. Without this or some equivalent "teeth," the DDR&E does not have the authority to effectively manage diverse efforts.

The project-oriented approach of the Defense Advanced Research Project Agency (DARPA) is the appropriate way to execute the new S&T projects, to be funded at $350 million per year above the current $200 million annual investment. Finally, the long-term research should be executed, not as a focused program, but by a broad range of institutions, loosely coordinated in their efforts, as is the case today.

Recommendation #2
Managing S&T Initiatives

The USD (AT&L) should

- Establish single focal point for biological warfare defense S&T.
- Reinstitute the Format-I to provide muscle for the DDR&E to effectively control focused ongoing S&T programs

PROCESS IMPROVEMENTS IN THE S&T ENTERPRISE

There is an imperative related to each of the transformational challenges: the need to capture and exploit technological advances that are progressing largely in the commercial world—and that are progressing at great speed. In some cases, such as for the biological sciences, these are commercial communities with which the Department of Defense has few ties or long-term relationships. Technology is pushing the Department to think differently, to use information and products in new and different ways, to explore ideas that may challenge traditional concepts.

The Department's science and technology enterprise must become more agile, more flexible, and more adaptive to be effective in this challenging environment. It must establish new ties with new communities. And most importantly, it must take a fresh approach to

technology transition to be more responsive to the rapid pace of change elsewhere in the world.

Over the last decade, the Defense Science Board alone has conducted nearly three-dozen studies on improving processes in the S&T enterprise. Topics have included strategies related to the technology base, the DoD laboratories, technology transition, commercial industry participation, access to commercial technology, ACTDs, and acquisition and procurement. Together these reports put forward a rich set of recommendations, most of which are still relevant today. What is needed now is implementation.

Drawn from this body of work, this task force has identified two areas that have the potential to transform the entire S&T, acquisition, and requirements process. They are

- Assuring access to developing ***commercial technology.***
- Adopting an ***integrated process*** of operational experimentation, spiral development, and transition of technology to users.

In addition, the task force believes it is important to comment on and make suggestions regarding one long-standing and much-studied problem: ***rejuvenation of the DoD laboratories***.

The following sections summarize the task force views and recommendations on each of these issues. Addressing them can significantly improve the effectiveness of the DoD S&T investment.

ACCESS TO COMMERCIAL TECHNOLOGY: RECOMMENDATION #3

The Department of Defense no longer leads the development of technology in many important areas, such as information technology, biology, and microelectronics. Nonetheless, these commercial technologies are essential in enabling the nation's future military superiority. Because of its complex system of procurement regulations and processes—such as accounting and information system requirements—the Department continues to deny itself access to many industries.

To improve access to commercial industry and ensure continued exploitation of commercially developed technology, the task force recommends a three-pronged approach. First, DoD must provide the incentives within the Department to turn to commercial products,

practices, and processes as the norm rather than the exception. To have real impact these incentives should focus on the program managers, who work directly with commercial industry. Second, the Department must reduce the barriers, identified in many past studies, which inhibit commercial firms from working with DoD contractors and with the DoD directly.

Finally, the Department must foster relationships and create new incentives with critical technology sectors to motivate them to apply their knowledge and people to critical national security challenges. In particular, DoD must find ways to work more closely with the biotechnology and pharmaceutical industries, research institutes, and other government agencies engaged in biological research. The Department needs to take advantage of the current Secretary's understanding of the pharmaceutical industry and the task force believes the Secretary must take the lead. In addition, the Secretary needs to forge a relationship with the Secretary of Health and Human Services (HHS). The National Institutes of Health and Center for Disease Control, both agencies of the Department of Health and Human Services, and DoD should begin to work together more closely, particularly in addressing elements of biological warfare defense.

Recommendation #3
Access to Commercial Industry

The USD (AT&L) should

- Mandate commercial practices, tools, techniques, components, software, and materials in DoD systems by establishing commercial technology as the norm; require justification for DoD-specific technology.
- Develop and implement acquisition processes that remove barriers and create incentives for commercial corporations to support DoD.

The Secretary of Defense should

- Personally engage with the biotech and pharmaceutical industries to build relationships with DoD and create effective partnerships.
- Forge a close relationship with the Secretary of HHS.

AN INTEGRATED PROCESS

Potential adversaries have increasing access to the most advanced technologies from global and commercial sources in much the same timeframe, as does the Department of Defense. The Department must dramatically improve its S&T and acquisition processes or risk being out-paced by its adversaries—which at its extreme could result in the United States facing opponents with more advanced capabilities in critical areas.

The current technology transition process involves four separate and distinct communities: science and technology, acquisition, test, and user. Each of these communities has different people, different mindsets, and are funded from different program elements. Real cooperation is the exception rather than the rule. More the norm is a process best characterized as "over the transom" rather than one of spiral development and collaboration, as discussed below.

Within this environment, ACTDs provide some opportunity for the S&T and user communities to work together. But there is weak involvement by the acquisition and test communities, and programs tend to go directly from an ACTD into the System Design and Development acquisition phase. In some cases more accelerated acquisition would be at least as effective and yet more cost-effective. Operational experimentation and spiral development, properly executed, force a more integrated approach and provide the basis for an improved technology transition process.

Operational Experimentation: Recommendation #4

Operational experimentation addresses all three elements of the military transformation process—changes in organization of forces, changes in doctrine and tactics, and changes in technology. Experimentation is quite different from exercises, training, and demonstrations. Experiments are typically small, with only tens to hundreds of participants. They are supported by extensive use of simulated capabilities and are conducted in an environment that encourages risk taking and considers learning to be the definition of success. The value of experimentation is to pursue many options and ideas and to provide a forum for collaboration between the operational warfighter and technologists.

The Department needs to form experimental units in each of the Services and at the joint level. These units should consist of dedicated command staffs and equivalent dedicated operational red teams or opposing forces. Other forces would be assigned to these units,

appropriate to each series of experiments. The technology of massive multi-player environments, discussed previously, could play a significant role in this process.

Spiral Development

Spiral development is an iterative process that links users to developers through an approach that is common commercial practice for continuous development and deployment of both software and hardware. The concept is to explore many technology options via experiments and ACTDs. Those that demonstrate promise are rapidly deployed to the field in limited quantities as "Block 1" systems. Inherent in the process is that the systems are likely to contain some weaknesses in the Block 1 deployment, but increasing capabilities will be fielded in subsequent "blocks" through a continuous development process.

The advantages of spiral development are many: more rapid deployment of advanced systems, lower cost development at lower risk, and a larger number of generated and demonstrated technology options. Spiral development has been institutionalized in directives by the Under Secretary of Defense for Acquisition, Technology, and Logistics and the Vice Chairman, Joint Chiefs of Staff, but it is a process that has yet to gain the kind of widespread use that the task force encourages.

Recommendation #4
Operational Experimentation

The CJCS should

- Form experimental units in each Service and Joint Forces Command.
- Form corresponding, dedicated operational red teams.
- Assign senior points of responsibility for fostering operational innovation and full use of experimentation.
  - Suggest Vice Chiefs and J-8 with accountable responsibility

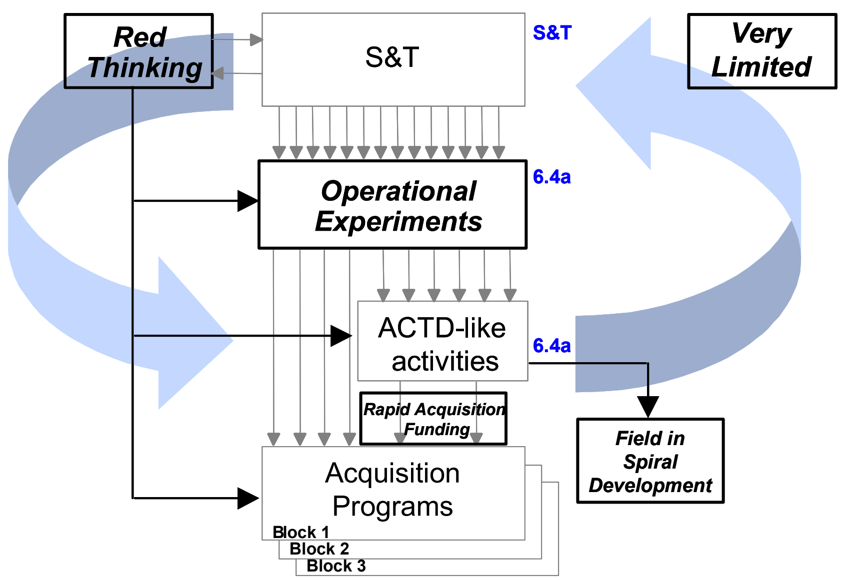
The USD (AT&L) should

- Provide funds for Joint and multi-Service experimentation.
- Fund and support increased use of ACTDs.

A New Technology Transition Process: Recommendation #5

The science and technology and acquisition processes need to be considered as a single enterprise not as individual entities that handoff a product from one to the other. Within this enterprise, the purpose of the science and technology community is to generate options and opportunities for the warfighter. These options are tested in operational experiments where their military value and usefulness can be assessed. Some experiments will transition to ACTD-like activities and others will spawn acquisition programs directly. The current process is illustrated in Figure 1-5, where the entries in bold are occasionally included but more often are not. In addition, while the USD (AT&L) has strongly encouraged shortening the time between Milestone A and Milestone C from five to seven years, this is persuasion rather than law.

Figure 1-5. Current Technology Transition Process



The task force believes that significant changes are needed to more closely integrate operational experimentation, spiral development, and technology transition. These changes will create technology pull for the S&T base and provide a path for technology to reach the user.

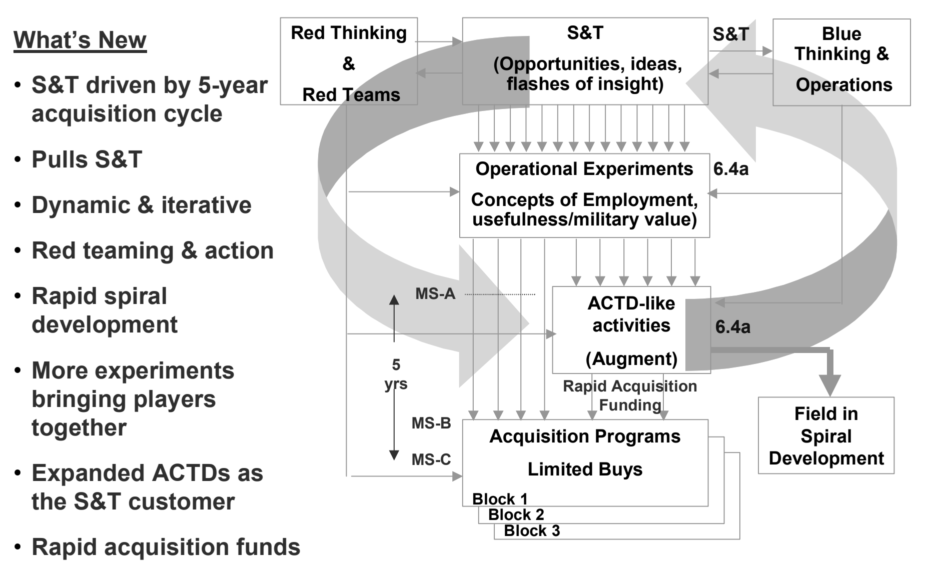
First, S&T should be driven by a 5-year acquisition cycle. The five-to-seven-year acquisition process suggested by the USD (AT&L) should be mandated as a five-year rule. The shorter timeframe will alter the

dynamics of the whole process and create a sense of urgency in the entire enterprise. Today the S&T community has limited coupling to the warfighter and acquisition communities, and what does exist is relatively artificial. So a "pull" for S&T from these communities is critical to a more dynamic and iterative processes.

Another critical element is red teaming throughout the process—using a smart adversary to challenge all concepts. Within the process, rapid spiral development and operational experimentation are inseparable. The task force also believes that ACTDs needs to be expanded as a customer for S&T development and a vehicle for promoting early involvement of the users.

This new technology transition process, illustrated in Figure 1-6, will outpace old habits. In particular, the current inherent delay in transition of two and one-half years that results from the Planning Programming and Budgeting System (PPBS) cannot be tolerated. The Department must work with Congress to provide flexible funding to proceed immediately to acquisition for promising programs. Such an initiative would be similar to the Rapid Acquisition Program (RAP) authority granted to the Army.

Figure 1-6. A New Technology Transition Process



The newly created Force Transformation Office can play an important role in implementing a more integrated technology transition process. The task force has identified three specific areas. First, the transformation office can be the advocate to foster real experimentation. It can be a focal point for coupling S&T products to the warfighters, identifying and supporting worthy experimentation candidates, and providing focus for joint and multi-Service experimentation in close cooperation with Joint Forces Command (JFCOM). This office could also take responsibility for ACTDs and in doing so be well positioned to exploit potential synergies between experiments and ACTDs. Finally, the office needs to have available, rapid acquisition resources to "pull forward" promising results from experiments and ACTDs.

Funding required for this process is modest. The task force recommends new "6.4A" funding for experimentation and transition activities, growing over several years to $1.4 billion. This is the total budgetary increase that applies to implementation of all process recommendations in this report. This amount would include $200 million per year to sponsor operational experimentation, supplementing Service experimentation funds with an emphasis on joint efforts. Resources for ACTDs need to grow to $1 billion per year, double current funding. The resources for ACTDs would include new 6.4A funds to replace current 6.3 ACTD funding, previously discussed, with approximately $250 million of the $1 billion in OSD and the remainder in the Services.

Finally, the task force recommends $200 million in funding to "bridge the PPBS gap" for rapid transition of successful ACTDs and experiments; this investment would supplement the current $150 million of RAP.

The task force believes that these resources can be generated from recent and proposed changes in the acquisition cycle and that they will lead to faster development at lower risk. The additional funds recommended represent less than 5 percent of the Department's current total development funds.

Technology is changing rapidly and requires a more flexible, and responsive process of transition to the user. The task force believes that the changes described will have the needed results.

Recommendation #5
New Transition/Acquisition Process

The USD (AT&L) should

- Implement new process outlined for innovative concept development, red teaming, and expansion of ACTDs.
  - Mandate 5-year acquisition cycle.
- Give Director of Transformation responsibility for joint operational experimentation, ACTDs, and transition
- Provide 6.4A funds to be the catalyst of change.
  - New funds growing to ~$1.4 billion per year.
  - Approximately $650 million under direct control of Director of Transformation and balance in ACTDs under Services.

Responsibility for Joint Research and Development: Recommendation #6

A more integrated technology transition and acquisition process is critical and will lead to major improvement in rapidly fielding advanced systems. But there is a special case in the technology transition area that requires further action: the lack of a joint development organization for critical joint warfighting capabilities. Three areas where the problem has become acute are joint command and control; joint intelligence, surveillance and reconnaissance; and biological warfare defense.

Without a joint development organization, there is no customer pull and there is no integrated approach to systems or solutions. And perhaps most important, there is no support to the warfighters in their primary area of concern—command, control, communications, and computers and intelligence, surveillance, and reconnaissance (C4ISR). While this problem has been long recognized, little progress has been made.

The task force’s recommendation for joint C4ISR is to assign responsibility for research and development to Joint Forces Command. JFCOM would be the focal point for developing and testing prototypes using spiral development. It would work with the regional Combatant Commanders to transition and tailor capabilities to each. To facilitate this task, JFCOM needs technical, system engineering, and acquisition capabilities and partners. Partnership with DARPA can facilitate a flow of new technology. A systems engineering capability at JFCOM would provide configuration control and other system engineering functions. A

Joint Program Office needs to be created to acquire and deploy systems. And partnership with a Federally Funded Research and Development Center could provide technical support. This approach is consistent with recommendations in prior DSB studies and by the Transformation Task Force established by Secretary of Defense Rumsfeld.

Similarly, and as discussed previously, DTRA should be the single point responsible for biological warfare defense R&D and acquisition. DTRA would operate in a mode similar to that of DARPA, drawing on talent in the Services, universities and industry. DARPA should continue to operate with the freedom to pursue high-risk, high-payoff projects as DARPA management sees fit. DARPA efforts would not be under the centralized DTRA control but obviously must be coordinated with DTRA which will continue to play an important role in achieving overall capabilities for biological warfare defense.

Recommendation #6
Responsibility for Joint R&D

The Secretary of Defense should

- Establish organizations and activities responsible for joint R&D and acquisition in C4ISR.
  - JFCOM and a Joint Program Office (co-located)
  - Adequate technical and acquisition support
- Establish single point responsibility for biological warfare defense R&D and acquisition at DTRA.

Rejuvenating the DoD Laboratories: Recommendation #7

Research and operation in the 84 DoD laboratories consumes about $2.5 billion dollars a year of the Department's S&T budget, approximately 28% of the total. The laboratories also manage another equivalent amount of DoD S&T. So, in total, the laboratories expend about 56 percent of the total S&T budget. In addition, they manage another $11 to 12 billion of non-S&T money. Some 25,000 personnel work in the laboratory system, including the Research, Development and Engineering Centers. It is clear that the DoD laboratories are an important part of the Department's S&T enterprise and require special attention.

Numerous prior studies have looked at the DoD laboratory system, identifying serious problems. Some of the most pervasive and debilitating problems include an inability to attract and retain quality people, an aging workforce fast approaching retirement, and personnel systems that place

many restrictions on dealing with poor performers. However, few of these studies have focused on the diverse nature of the laboratory functions as a basis for rejuvenating the laboratory system. Much of the activity conducted in the labs, and the majority of funds expended in or flowing through the labs, is not related to S&T. The labs are involved in engineering development, testing, in-service support and engineering, and acquisition support.

The task force believes that the Department should conduct an in-depth review of each of the DoD laboratories to review its activities, understand its functions, and understand its workforce. With this information, the laboratory structure can be significantly reshaped. Personnel, activities and facilities involved in acquisition can be transferred into acquisition organizations. Laboratories with a strong S&T or technology orientation, with significant in-house research, should be moved to university management to relieve them from the restrictions of the civil service personnel system. Other labs might be considered for privatization, consolidation, or closure. This review should begin immediately and conclude in nine months with specific recommendations for each laboratory. Implementation should conclude by 2005.

Whether or not the Department chooses to undertake such a review, the task force believes the recommendations of the most recent study of the laboratories by the Defense Science Board, *Efficient Utilization of Defense Laboratories*, should be implemented.[7] This study reviews and consolidates recommendations of many prior studies and focuses on personnel and quality improvements. Implementing its recommendations is essential to improving the laboratory system.

[7] *Report of the Defense Science Board on Efficient Utilization of Defense Laboratories* (Washington, DC: Office of the Under Secretary of Defense for Acquisition and Technology), October 2000.

Recommendation #7
DoD Laboratories

The USD (AT&L), with direction of the Secretary of Defense, should instruct the DDR&E to

- Review each laboratory in detail and determine individual courses of action, to include the following:
  - Administrative personnel transfers.
  - University management.
  - Privatization, consolidation, or closure.
- Complete review and begin taking action within 9 months with end goal of 2005.
- In any case, especially for those likely to remain status quo, implement recommendations of most recent DSB study.
  - *Efficient Utilization of Defense Laboratories*, October 2000.
  - Focus on personnel and quality improvements.

FINAL THOUGHTS

Two challenges will fundamentally change the nature of the S&T enterprise and military capability:

- Rapid technology transition: time matters.
- Transformation to new ways of fighting.

Technology is one enabler of new military capabilities and is typically most effective only in the context of new concepts of operations and doctrine. To accomplish both transition and transformation the Department must change its S&T enterprise through operational experimentation, rapid spiral development, and evolutionary acquisition. Only then will the Department be able to fully realize the benefits of the S&T investments described in this report.

In summary, the recommendations of the task force focus on transforming the Department's S&T enterprise. The primary recommendations have been discussed in this chapter; supporting recommendations are contained in the remainder of this report. The recommendations fall in seven areas:

1. ***Invest in new S&T initiatives in support of four transformational challenges***: defending against biological warfare, finding difficult targets, making timely, accurate decisions, and enabling high-risk operations. Expand and provide more focused management for ongoing related S&T programs.
2. ***Maintain the level of S&T investment at 3 percent of the overall DoD budget as currently planned by the Department.*** Provide additional funds for new S&T priorities by reprioritizing current programs and shifting funds for ACTDs to the 6.4A account.
3. ***Exploit commercial technology*** through expanded use of commercial products and processes; elimination of barriers; and efforts to forge relationships with commercial industry.
4. ***Foster operational experimentation***, as an integral element of a new S&T enterprise, through assigned experimental units and sustained senior attention.
5. ***Establish a new technology transition process*** by vesting responsibility for joint operational experimentation, ACTDs, and technology transition with the Director of Transformation.
6. ***Accelerate the transition process for joint R&D*** by establishing points of responsibility in joint C4ISR and biological warfare defense.
7. ***Restructure the DoD laboratories and rebuild the scientific and engineering workforce*** based on a major review of the function and workforce in each laboratory.

Funding for the full implementation of all recommendations of this report is modest. Expanding existing programs and conducting new S&T initiatives to support transformational challenges should eventually require additional investment of $1.8 billion annually. These funds should be found by reprioritizing within the S&T program. Funding for operational experimentation and technology transition should grow to $1.4 billion per year over the span of several years. This amount represents less than 5 percent of the total DoD development funding.

The task force believes that implementation of these recommendations will provide an enormous improvement in the focus and effectiveness of the defense S&T enterprise. The task force believes that that this report identifies those changes that offer the greatest beneficial impact today.

CHAPTER II

MILITARY APPLICATIONS

American warfighting doctrine emphasizes the employment of technology and firepower to achieve decisive battlefield victory while, at the same time, minimizing casualties and collateral damage. This approach has long driven the Department's science and technology community to seek the most advanced weapons and systems technologies—with great success. The Cold War was won by superior technology and ready forces developed and deployed over a fifty-year period. Since 1990, new operational commitments have created a new set of technology demands to enable the conduct of effective combat operations in all terrain and climatic conditions, against the full spectrum of modern threats.

These new demands on the S&T enterprise are explored in this chapter. First the chapter examines the many factors that influence military needs. Based on this assessment, nine high-priority military needs are identified and described, focusing on the science and technology efforts that will be required to attain new capabilities. Among these nine are the four transformational challenges described in the previous chapter. Finally, the chapter addresses the challenge of improving the interface between the science and technology and operational communities. It closes with conclusions and recommendations related to these topics.[8]

ANALYTIC APPROACH

The analysis in this chapter is based on a wide range of inputs from across the national security community. Two days of interviews were conducted with the combatant commanders (or their immediate subordinates) and selected senior operational commanders, based on a detailed questionnaire used to stimulate discussion and interaction. These discussions addressed operational deficiencies along with specific technical solutions that might be explored—all with an emphasis on operational realism.

Views were solicited from a wide range of administration officials including the military services, Joint Staff, and Office of the Secretary of Defense to gain insight into the Department's concepts and plans for future forces. Because the Secretary of Defense Strategic Reviews and the

[8] This chapter reflects the work of and was prepared by the Military Applications Panel of the 2001 DSB Summer Study task force. The panel members consisted of a mix of military experts with Joint and Service experience at senior levels as well as technical experts with experience in defense research and development. The panel membership, along with the government advisors and staff who contributed to this effort, is contained in Annex B.

Quadrennial Defense Review were in progress during the course of this study, special attention was given to the views being considered in those activities.

Meetings were also held with a number of independent defense experts and theoretical analysts deeply involved in studying the current trends in military affairs. In addition, a historical review provided insight into periods of significant organizational and operational change within the military as well as periods of significant technological advancement in warfare.

Finally, to ensure full understanding of the operational implications of the most advanced technology concepts currently in early development, a review was conducted of several programs with the potential to have profound impact on military operations. These programs include the Unmanned Combat Air Vehicle, the Future Combat System, and the DoD robotics program.

IDENTIFYING MILITARY NEEDS

National security policy drives military posture. The operational priorities that emerge in turn drive the S&T investments needed to maintain the superior technological edge held by the United States across a wide span of military missions. These missions include (1) strategic deterrence and missile defense adequate to support a nuclear deterrence policy and protect the nation from limited attack; (2) power projection to support U.S. foreign policy; (3) special operations, peacekeeping, and counter-terrorism; and (4) assured access to and use of space and denial of use to adversaries.

This traditional and broad view of military missions is by itself inadequate to determine military needs. The task force tried to reach a deeper understanding of the operational basis for science and technology investment decisions. Thus, in deriving priorities for military needs, the task force sought to understand the following seven factors:

- What most worries current combatant commanders?
- What must the Services do well operationally?
- Where are the consequences of operational failure unacceptable?

- What is necessary to enable future operational concepts?
- What dangers do adversary threats pose for operational capabilities?
- What technological advancements will strongly influence global military capabilities?
- How will current and emerging technologies actually affect warfare?

These factors need to be considered in formulating a sound set of military needs. Synthesizing the answers to these questions provides the basis for S&T investment priorities.

FACTOR 1: WHAT MOST WORRIES CURRENT COMBATANT COMMANDERS?

The concerns of the combatant commanders provide insight into specific details of essential military missions and infuse operational realism into the task force's considerations. The joint field commanders are on the front line, poised and prepared with ready forces to engage when directed. They have responsibility for security, planning, and force readiness. They constantly monitor intelligence information describing risks to U.S. interests around the globe. These and other characteristics make the combatant Commanders credible speakers regarding current and future U.S. force strengths and vulnerabilities.

The most significant concerns expressed by the nine senior representatives of the combatant commanders interviewed were:[9]

- Joint Command C4ISR. (9 of 9)
- Prompt and accurate target detection. (8 of 9)
- Integrated remote sensing. (7 of 9)
- Platform survivability. (7 of 9)
- Assured ability to deploy forces. (Continental United States only; 2 of 2)

The nine representatives of the combatant commanders unanimously agreed that Joint Command C4ISR is a critical concern; there is a need for integrated communications and sensors that are secure, assured,

[9] This list summarizes the areas of concern as expressed by the nine combatant commanders (or their representatives) interviewed. Annex D contains the questionnaire provided in advance of the interviews.

connected, deployable, exercised, and ready for employment. The need to find, identify, and track difficult targets—both fixed and mobile—in all weather conditions was a near universal concern. Consistent with this need was the desire for integrated remote sensing to support targeting and situational awareness of the battlefield, whether on the ground, in air, on or under the sea, or in space.

Equally important is the need for platform survivability. The specific nature of this concern depended on the specific responsibilities of the Commanders, but was of interest across the board. Concerns over threats to survivability included counter-measures of various types such as electronic warfare that could defeat U.S. warfighting capabilities; frequency interference; network attack; and the ability of adversaries to detect some platforms, making them vulnerable to active defenses. Finally, the two combatant commanders in the Continental United States (CONUS) expressed concern about the impact of certain threats—including terrorism and the use of biological weapons—on the ability of U.S. forces to mobilize and deploy to engagement locations.

Factor 2: What the Military Must Do Well Operationally

U.S. forces will have to continue to perform certain operational missions, now and into the foreseeable future. These missions include:

- ***Achieving and maintaining air-superiority over friendly and hostile airspace***. Air superiority is paramount for U.S. conventional forces. The United States has not fought without air superiority for several decades, and is unlikely to do so on any significant operational scale. Without air superiority, the capability to deploy, support, and sustain U.S. forces is compromised.
- ***Controlling sea lines of communication***. The military cannot move and sustain sufficient force by air alone, so the ability to move and supply by sea is essential. Recent operations in the Persian Gulf, off the coast of Africa, and in the Balkans all relied on access to sea-lanes of communication.
- ***Conducting effective strike operations***. American warfighting operations depend heavily on the use of air-delivered strikes. When effective, it is a preferred mode of operations. When air power alone is not enough to achieve an objective, it is used extensively as a precursor to ground

maneuver and in conjunction with ground operations. Because air campaigns can extend for weeks or even months, the rate of loss of aircraft must be kept small (under one percent a day for a protracted campaign).

- ***Deploying and supporting ground forces for a variety of operations***. The United States must be able to move and support ground forces for missions ranging from forced entry and protracted combat operations to peacekeeping and humanitarian assistance. The ability to arrive in a theater of operations quickly and set the conditions of the battlefield requires forces be fully trained and readily deployable. While the acceptable time frame can be debated, rapid deployment is essential.

- ***Operating in a joint and combined force with political constraints***. U.S. forces will almost always operate in a joint and combined context with allies and partners. Most modern operations—such as the Gulf War and the campaign against Yugoslavia—were conducted with political constraints that influenced the scope of the operation and the acceptable levels of violence or collateral damage. These constraints can be onerous to operators but will continue to exist as long as U.S. forces remain an arm of American foreign policy.

- ***Constraining collateral damage to acceptable levels***. Across the operational mission spectrum, from long-range interdiction bombing operations to peacekeeping and peace-enforcement missions, U.S. forces will continue to be politically constrained by limitations on collateral damage—although some level of collateral damage will always be unavoidable.

- ***Avoiding large-scale and protracted casualties***. U.S. commanders will also be obliged to minimize risk and harm to U.S. forces. In situations where vital interests are at stake or the nation is in direct risk, the tolerance for casualties will prove higher than when the mission's importance is less clear, as in the Somalia experience. The Gulf War created the myth that large-scale conflicts can be fought with minimal casualties, and many now believe that this is always possible.

FACTOR 3: UNACCEPTABLE FAILURES

Failure is unthinkable in some mission areas, and developing force capabilities to support those missions is a high priority.[10] The task force identified four events for which failure of defense is unacceptable: (1) attack on the continental United States using weapons of mass destruction, (2) attack on U.S. installations overseas using weapons of mass destruction, (3) denial of access in areas of vital interest overseas, and (4) the rise of a major competitor capable of defeating U.S. forces conventionally.

The first two of these events would involve the high casualties associated with employment of weapons of mass destruction, primarily nuclear and biological weapons. For the foreseeable future, the United States will rely on deterrence to prevent nuclear attack. As technology matures, it may increasingly rely on defenses, at least for delivery by ballistic missile. Technology should certainly be explored and fielded if it matures. Biological threats are a more complex problem because of their wider availability and the ability to deliver them covertly by a variety of means.

On the conventional side, U.S. integration in an increasingly global trading economy and its need for access to overseas energy sources are compelling arguments for continued overseas basing and access on a routine basis. While the emergence of a peer competitor with the power to defeat the United States by either nuclear or conventional means is not likely in the near term, the United States must work to ensure such a capability does not emerge in the medium or long term.

FACTOR 4: ENABLING FUTURE OPERATIONAL CONCEPTS

Each of the military Services is developing and implementing new concepts for forces and warfare, as depicted in Figure 2-1, which are influenced by the Department's joint-warfare vision.

[10] This study was conducted and completed prior to the September 11, 2001 terrorist attacks. Perspectives on many issues discussed in this chapter would likely be influenced by those events, but on the whole the task force believes its conclusions remain valid.

Figure 2-1. Military Service Future Force Concepts

The viability of future operational concepts is directly related to whether technological advances will provide the means to fulfill these visions. The joint perspective, which is discussed first, provides an overarching context for the individual Service visions, which are addressed in turn. The unique management problem of S&T and acquisition to support joint command and control is also discussed here.

Joint Warfare: Joint Vision 2020

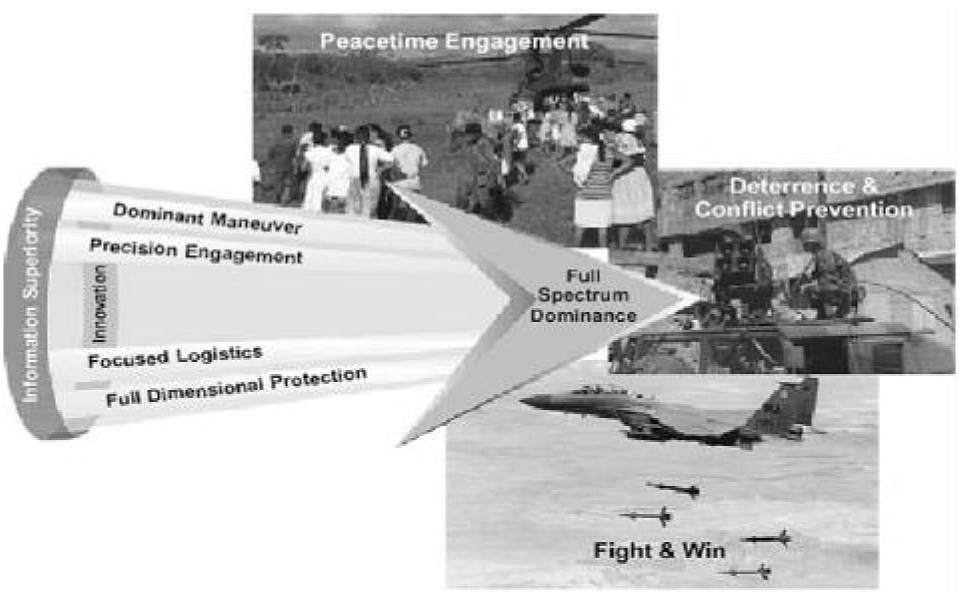
The U.S. military must be a joint force capable of full-spectrum dominance. Implementing this vision requires optimal integration of all joint forces and effects. Its basis is four-fold:

- The global interests of the United States and the continuing existence of a wide range of potential threats to those interests.

- The central role of information technology to the evolution of not only the U.S. military, but also the capabilities of other actors around the globe.
- The premium that a continuing broad range of military operations will place on the successful integration of multinational and interagency partners and the interoperability of processes, organizations, and systems.
- Reliance on joint forces as the foundation of future U.S. military operations.

In Joint Vision 2020, the operational concepts established in Joint Vision 2010 remain key—dominant maneuver, precision engagement, focused logistics, and full-dimensional protection—as Figure 2-2 illustrates. The vision confirms the direction of the ongoing transformation of operational capabilities. It emphasizes the importance of further experimentation, exercises, analysis, and conceptual thought, especially in the areas of information operations, joint command and control, and multinational and interagency operations. Joint Vision 2020 addresses the full range of military operations—but warfighting remains the primary focus.

Figure 2-2. Joint Vision 2020



Changes in organization and doctrine require both technological and intellectual innovation. Key S&T needs include C4I technology to support integrated joint operations; wide-area sensing for a common operational picture; and decision support technology for collaborative planning and execution.

The Unique Case of S&T for Joint Command and Control

Despite their importance to operations, joint needs tend to suffer considerably in the S&T investment allocation process. The lack of a "customer" for S&T in a number of critical areas means that there is no demand or "customer pull" for new technology. Thus, supporting S&T programs are not executed, and technology transition to support joint needs is slow at best. The need for an integrated joint command and control and a joint intelligence, surveillance, and reconnaissance, (ISR) suite is critical to effective joint operations and deserves special mention. The combatant commanders confirm that this requirement is a priority.

When directed to employ joint forces, a joint field command is formed and tailored to the specific mission or tasking—such as Desert Storm, Bosnia, or Kosovo. Essential to employing joint forces, especially in the critical early stages of a mission, are effective joint command and control of assigned forces plus supporting communications and computer interlinks and databases. A ready, trained, exercised, and demonstrated joint-command element is fundamental to operational effectiveness. Yet, the United States lacks such a capability today. Instead, command and control and ISR assets are integrated for use at the time and point of need, which means that systems are put together in ways that can be and have been demonstrated to be detrimental to effective operations.

C4ISR assets are procured and owned by the Title 10 services and provided, when needed, to a joint field command. The joint command "assembles" its joint C4ISR suite as assets are provided, usually during the early hours of an unfolding crisis. In general, these service-provided C4ISR capabilities have been procured over an extended period of time, based on individual service needs and resource availability. As a result they fit into service architectures that may or may not be interoperable with the systems and processes of other services. Integration challenges range from reconciling unrelated waveforms and entirely different frequency operating bands to trying to link software with incompatible formats and overcoming conflicting network protocols. While joint standards and protocols are being put in place in the acquisition community, they primarily apply to new procurements. The connectivity

problems that exist today will continue well into the future—at least until one generation of procurements has elapsed.

In addition to being a serious interoperability challenge, the lack of an effective approach to joint C4ISR creates other problems as well. The joint commander is responsible and accountable for exercising command and control over the assigned service forces but does not determine what assets will be available. This is a serious command weakness, if not vulnerability, particularly in the early hours of a crisis. Jointly organized field commands appointed, and often immediately deployed, to deal with the designated national security crisis need pre-crisis assurance of what particular C4ISR assets will be made available upon demand, intimate familiarity with the to-be-provided C4ISR hardware and software (through pre-crisis exercising with the personnel who will be accountable for exercising joint command and control), and finally, demonstrated pre-crisis C4ISR interoperability among the assets to be provided.

An alternative solution—particularly attractive from a command accountability perspective—might be to provide sufficient C4ISR funding directly to geographic combatant commanders for them to build their own deployable joint C4ISR systems, tailored to their missions. The Department would have to either set aside existing funds for these procurements or seek new procurement authorities to direct congressional funding for joint C4ISR to newly established geographic accounts for the combatant commanders. Combatant commanders would not require a full acquisition organization; capabilities and systems identified for joint C4ISR could be assigned to the Services for procurement using existing service acquisition capabilities.

Also needed is a core joint force command element that would be embedded in Joint Forces Command and used routinely in joint sponsored exercises to provide command and control and ISR support to assigned service elements. The challenge is to use technology to overcome fundamental incompatibility among Service-owned electronic communications, sensing, storing, and networking systems that would be incorporated into a joint command and control system. The task is substantial—requiring the use of existing joint communication and information protocols and standards as guides to invent and field decision-support tools that merge, integrate, display and move otherwise incompatible voice, electronic, and data streams across the full range of communication needs. Solutions need to be operationally tested as they emerge, providing prompt and necessary feedback to developers as to the potential for success. Once systems are fielded, the joint force command element would be accountable to train frequently and exercise with an

array of Service-provided C4ISR assets to ensure competence and familiarity in their integration and employment.

In today's environment, the lack of a customer means that there is no interface between the S&T, acquisition, and operational communities to provide essential feedback during the development and operational testing processes. A solution to this problem will require a commitment by the Office of the Secretary of Defense and the Joint Chiefs to a standing joint command and control and ISR employment capability. Joint Forces command would be a logical component to own, experiment, train, operate, maintain, store, and ultimately employ a Joint C4ISR Command Element—thus creating a "customer" and "customer pull" for technologies to support these needs. The Office of the Secretary of Defense for Command, Control, Communications and Intelligence (OSD(C3I)) could sponsor and fund the necessary research and development efforts, with DDR&E oversight and DARPA and the Director, Operational Test and Evaluation (DOT&E) as important technology partners.

The subject of joint C4ISR is addressed separately in other parts of this study. This issue deserves special attention here, despite the fact that it is as much an acquisition and management issue as it is one of science and technology. Without well-defined requirements, the S&T community must be involved in a leadership role in experimentation and concept exploration to provide the basis for acquisition efforts.

With the joint operational vision as a backdrop, the individual Service visions for future forces and operational concepts will be discussed.

Army: Objective Force

The Army is committed to developing a future force based on lighter vehicles and capable of being deployed by existing strategic and tactical airlift. This force is intended to meet all Army operational goals and be decisive in any combat mission. Because light vehicles are inherently less survivable, the Army intends to rely on future situational awareness and command and control systems to employ effects at extended range without relying primarily on concentrating forces for close combat.

The concept of the Army's objective force includes the following elements:

- Mass of effects, not forces.
- Simultaneous, brief, violent attacks in multiple directions.
- Attack, disengage, reorganize, and attack.

- Speed, situational awareness, robotics, and lethality together replacing mass.

In addition to relying on situational awareness and command and control to enable the massing of effects, the Army intends to rely on a very high operational tempo to prevent an adversary from mounting a successful defense or attack. Robotic systems are envisioned as part of the force concept, as are extended-range lethal systems designed to limit direct fire in close-in engagements.

The S&T needs required to support this concept are varied and include the following: unmanned air and ground systems; advanced sensors for air and ground; integrated real-time command and control and battle management; extended range precision munitions; advanced vehicle propulsion; and integrated survivability suites including signature management. Though not all-inclusive, this list captures essential capabilities needed to make the Army's Objective Force a reality.

The Army's plan includes an initial fielding in 2010 followed by block upgrades and pre-planned, product improvements. Continuing technology evolution and integration is central to the Army's approach. The Army's goal is to be able to deploy one division anywhere in the world in 90 hours and five divisions in 120 hours.

Navy: Network Centric Warfare

The United States Navy is undergoing a transformation to Network Centric Operations (NCO), which will enable the Navy to more quickly attain and sustain global access and to decisively influence future events at sea and ashore—anytime, anywhere. NCO will dramatically strengthen the Navy's ability to shape an environment, deter an adversary, and should deterrence fail, prevail in war.

The network centric concept is to be used as the organizing principle for developing future Navy forces. It effectively pairs networking and information technology with effects-based operations. NCO can be broadly described as the art of deriving maximum force power through the rapid and robust networking of diverse, well-informed, and geographically dispersed warfighters. Effective Network Centric Operations will enable a precise, agile style of maneuver warfare that can sustain access and decisively influence events ashore. NCO focuses primarily on the operational and tactical levels of warfare, but can have significant impact on all levels of military activity in conflict resolution—from the tactical to the strategic.

Network Centric Operations harness the power of on-going technological revolutions to dominate operational tempo and most rapidly achieve warfighting aims across the full spectrum of military operations. NCO requires an increased use of sensor networks and an improved understanding of an adversary's operational approaches to mass effects in a way that will have the most impact on an adversary's future course of action by limiting his options.

Four major supporting concepts underpin Network Centric Operations: gaining the information and knowledge advantage; assured access; effects-based operations; and forward sea basing. The required science and technology advances include: tiered and netted sensor grids above, on, and below the sea; linked manned and unmanned vehicles; robust joint C4ISR capabilities; decision aids and knowledge management capabilities; interface capabilities between man and machine; and efficient, high-speed and long-range surface and sub-surface platforms.

Air Force: Global Strike

The Air Force will meet the diverse challenges of the 21st century through a vision of global vigilance, reach, and power—a concept based on an integration of air, space, and information operations. The intent is to "exploit the full air and space continuum on a regional and global scale to achieve effects both on earth and in flight regimes beyond the horizon." A foundation of this capability is achieving decision dominance over the adversary through the fusion of a full range of information drawn from national and tactical means and rapid conversion of this information into decision-quality knowledge. The Air Force will provide the balanced air and space capabilities that are key to meeting national security objectives and realizing the full-spectrum dominance envisioned by Joint Vision 2020.

The Air Force will achieve its goals by enhancing its capabilities as an expeditionary force, configured for the full spectrum of operations. The Air Force has constituted 10 deployable Air Expeditionary Forces (AEFs)—two deployed or on call to meet current national requirements while the remaining train and prepare for future operations. The AEFs provide joint commanders with force packages that can be tailored to any contingency. The Air Force vision is to increase capabilities through innovations and adaptations that make these forces lighter, leaner, more lethal, and more responsive.

The Air Force can deploy an AEF fast enough to curb many crises before they escalate. In the near future, the Air Force will be able to rapidly deploy up to five additional fully capable AEFs in 15 days, thereby

providing joint force commanders options to begin offensive operations to halt and win major wars.

To achieve this vision, the Air Force will require advances in a number of areas. One requirement is the capability to horizontally integrate the full range of information in real time and rapidly convert that information to knowledge and understanding. Also required will be enhanced, adaptive, real-time precision targeting, which increases the number of targets that can be engaged; assured access to any target by overcoming anti-access strategies; and enhanced capabilities to quickly defeat enemy defenses. In addition, increasingly fast, flexible, responsive, and reliable support will be the foundation of all Air Force operations..

The integration of revolutionary technological developments and dramatically improved operational concepts and organizational changes led to profound increases in combat capability as seen in recent successes in Bosnia, Southwest Asia, Kosovo, and Afghanistan. Continuing transformation efforts promise even greater potential, as the Air Force continually transforms the way it approaches warfare. Assuring security and stability requires global vigilance, reach, and power—global vigilance to anticipate and deter threats, global reach to curb crises, and global power to prevail in conflicts and win America's wars.

U.S. Marine Corps: Expeditionary Maneuver Warfare

Expeditionary Maneuver Warfare (EMW) provides the philosophical basis for the Marine Corps execution of future operations. It describes Marine Corps operational capabilities across the spectrum, as they apply not merely to amphibious operations, but to all aspects of warfare in and around coastal waters. EMW is built on the twin pillars of maneuver warfare and the Marine Corps' expeditionary culture. The operational concepts that constitute EMW are operational maneuver from the sea, sustained operations ashore, and ship-to-objective maneuver.

Expeditionary Maneuver Warfare focuses the Marine Corps' designed competency and specifically enhanced capabilities in littoral warfare to ensure that deployed future Marine Air-Ground Task Forces will best support the Joint Force Commander throughout the spectrum of conflict. EMW capitalizes on innovation, experimentation, and technology.

The properties of EMW are: compatibility with joint and multinational missions, strategic agility, operational reach, tactical flexibility, and support and sustainment. Strategic agility implies rapid and fluid transition from pre-crisis to operational capability with forces that are ready, sustainable, and rapidly tailored for multiple missions.

These forces will be able to project and sustain force across the spectrum of conflict in conjunction with other forms of national power. The goals are overwhelming tempo and speed against an adversary and a responsive force in a non-combat scenario.

EMW will couple doctrine with technological advances in speed, mobility, fire support, communications, and navigation to seamlessly and rapidly identify and exploit enemy weaknesses across the entire spectrum of conflict. More specifically, S&T needs include: networked operational communications, information, and intelligence systems; global access capability to domestic and international information resources; high-speed lift; mine and obstacle countermeasures; and precision navigation.

FACTOR 5: DANGERS FROM ADVERSARY THREATS

In the next 15 to 20 years, the United States does not expect to face a peer competitor. There are, however, likely to be continued conflicts around the world involving U.S. interests. Responding to these conflicts will entail diverse global deployments in unpredictable environments. U.S. forces will continue to be engaged in the full spectrum of conflict conditions from peacekeeping to regional war. Facing the overwhelming capabilities of U.S. conventional forces, adversaries will exploit vulnerabilities in non-traditional ways, as Table 2-1 suggests. With individual national interests around the world likely to change over time, the United States cannot always rely on sanctuaries overseas, but must be prepared to employ force from the continental United States, sanctuaries far from the engagement area, and/or from sustainable maritime platforms.

Vulnerabilities

Potential adversaries with interests inimical to those of the United States, will search out U.S. vulnerabilities not only in military and security sectors but in other sectors of society as well. Adversaries who believe the United States might intervene to protect its interests abroad are seeking ways to frustrate or defeat the ability of the United States to respond to crises. Examples perceived U.S. weaknesses allowing possible exploitation include:

- Vulnerability to single-point critical failures.
- Vulnerability to catastrophic collapse of integrated network-centric systems.
- Insecurity of information systems.

Table 2-1. Example Vulnerabilities and Potential Counters to U.S. Military Employment Concepts and Capabilities

U.S. Concepts and Capabilities	Adversary Concept to Counter U.S. Strengths	Selected Non-technical Adversary Responses	Selected Technical Adversary Responses
Precision Strike	Reduce target signatures Deflect U.S. weapons Employ rules of engagement outside Geneva Convention	Distribute forces Hugging Non-nodal forces Human shields Embed military forces in civilian infrastructure	Camouflage Concealment and Deception (decoys, buried targets, multi-spectral camouflage & smokes) GPS jamming
Information Dominance	Disrupt, degrade U.S. capabilities Create own effective communications and intelligence	Deception Media manipulation Primitive comms (couriers) Better human intelligence	Information warfare (IW) techniques shared among adversaries Radio Frequency disruption Adversary capabilities: Cell networks Fiber optics Quantum cryptography Commercial space imagery UAVs
Force Protection	Create early, visible casualties	Suicide missions Terrorist-type attacks (against barracks, ships) Rumors of biological warfare (BW)/chemical warfare (CW) contamination Publicize casualties to CNN	Thermobarics Tandem RPGs Laser blinders CW/BW tactical use Cruise missile proliferation Low signature propellants for surface-to-air missiles
Dominant Maneuver	Prolong combat and/or hide and survive	Force urban combat Seek out complex terrain Ambush Attrition Obstacles	Hybrid (upgraded) ground systems, including APS, night visions Artillery-delivered high precision munitions
Assured Entry/Access	Delay or deny	Counter-coalition diplomacy and propaganda Occupy access points Hold civilians in targeted access areas	BW/CW against ports and airfields (CONUS or theater) Counter stealth, such as PCL, and other advanced air defense Advanced mines (naval and land) Advanced torpedoes, unmanned underwater vehicles
Focused Logistics	Disrupt	Deny host nation support	IW against automated logistics POL contaminants

- Over-reliance on fragile technologies such as the global positioning system or commercial communications capabilities.
- Possible unanticipated technological vulnerability of weapons and platforms.
- Inability to effectively operate with coalition partners and/or allies,
- Vulnerability in forced close combat, especially in urban terrain.
- Vulnerability to effective attack upon rear areas, especially the deployment, logistics, sustainment, and support infrastructure.
- Vulnerability and fragility of U.S. space assets.
- Broad use by adversaries of chemical and biological weapons, especially in civilian areas.
- Vulnerability to effective missile-defense countermeasures.
- Vulnerability to effective anti-access and preemptive strategies.

Daunting U.S. military capabilities force adversaries to respond creatively. They will consider U.S. strengths and weaknesses and will design approaches to avoid the former and while exploiting the latter. Careful self-assessment of existing and future vulnerabilities is essential in setting priorities to remedy them in an orderly fashion and with the least risk. Sound priorities will focus on areas where scientific and technological advances can most rapidly improve U.S. capability and reduce risk.

FACTOR 6: PROGRESSIVE TECHNOLOGIES AND MILITARY CAPABILITIES

Any prioritization of DoD S&T must take into account the full spectrum of military and commercial technologies being pursued around the globe. Critical is the challenge of understanding the direction of evolving technologies and the potential they may offer for improved U.S. military capability. The task force believes that the following list identifies those technologies most likely to advance military capabilities in the future—for both the United States and its adversaries:

- Continued growth in computing power, both hardware and software.
- High bandwidth wireless communications.
- Novel energetic materials.
- Sensor materials, including radio-frequency components and electro-optical and infrared focal plane arrays, in particular.
- New capabilities offered through exploitation of nanotechnology and microelectromechanical components.
- Biological detection devices and therapeutics.
- Unmanned systems.
- Commercially available space-based sensor systems.
- Active biological processes.

FACTOR 7: TECHNOLOGICAL ADVANCEMENT AND WARFARE

Finally the relationship between future warfare and evolving technology must be considered in identifying priorities for S&T investment. Predicting, in peacetime, the optimal blend of organizational structure, operational concepts, and technology for future conflicts is always challenging. The best blend of the three has historically been verified only by actual experience. Modern simulation and modeling tools, however, provide a new opportunity to fully explore options in peacetime.

At all levels of the S&T development process, modeling, simulation, gaming theory, and war games should be used extensively in seeking out useful insights, framing new concepts, and developing new and alternative lines of scientific inquiry. This effort can also be extremely useful in helping to educate end users, especially operational military personnel, in the art of the possible before it can be demonstrated in the field or used in actual combat.

This approach will also help to create “technological buy in” by military institutions, which are often slow to change in the absence of clear evidence of the failure or inadequacy of current concepts and capabilities. The military has a tendency to use technology to do things the same way, only better. Yet, the highest operational payoff is often in doing new things or in doing old things in a totally different way. Today,

there is a great deal of creative thinking driving the transformation of the U.S. defense establishment.

Modern technology has already had a significant effect on the battlefield and the nature of warfare. The increased lethality of modern munitions—a result of improved range, precision, and energy—is outpacing the survivability of nearly all systems. Reliance on extended-range engagement is emerging as a preferred and possibly dominant method of warfare for strategic, air, naval, and ground operations. Yet, as technology becomes increasingly available around the world, potential adversaries will gain capabilities that will enable them to defend against U.S. power. Even more worrisome is adversary exploitation of weapons of mass destruction—conventional, chemical, biological, and radiological—that has the potential, especially in the near term, of severely crippling not only U.S. military capability but the nation as a whole.

Looking ahead, the next-generation battlefield will rely on a number of emerging concepts enabled by new technologies, such as

- Assured situational awareness and communications.
- Highly automated operations including human control with software decision aids and highly collaborative dynamic operations.
- Reliance on extended-range fires in all warfare regimes.
- Reliance on unmanned systems for high-risk missions and tasks.

HIGH-PRIORITY MILITARY NEEDS

By assessing and synthesizing the "key considerations" described in the previous section, the task force derived nine high-priority military needs. In order to realize new operational capabilities in these areas, the Department will need to make focused investments in science and technology. The high-priority military needs are as follows:

1. ***Biological warfare defense*** for immediate detection and defeat.
2. ***Capability to find and correctly identify difficult targets***, both static and mobile, which involves the ability to target

adversary tactical forces for standoff engagement by air, land, or from the sea.

3. ***Timely, accurate decision making*** that effectively integrates joint and combined command, control, communications, computers and intelligence (C4I) systems to support operations at all levels.
4. ***Support of high-risk operations*** with systems such as unmanned systems capable of high-risk tactical operations.
5. ***Missile defense*** that is cost effective with low leakage against tactical and strategic missiles and unmanned aerial vehicles.
6. ***Affordable precision munitions*** that are resilient when subjected to countermeasures.
7. ***Enhanced human performance*** that overcomes natural limitations on cognitive ability and endurance.
8. ***Rapid deployment*** and employment of forces globally against responsive threats.
9. ***Global effects*** that can be delivered rapidly, anywhere.

In the sections to follow, these nine military needs are discussed. For each, the task force examines the basis of need, identifies the technology required to advance U.S. capabilities, identifies potential vulnerabilities and risks, and describes the goals and approach of an effective S&T initiative.

1. Defending Against Biological Warfare

The biotechnology revolution has profound implications for biological warfare defense. While the United States, along with many other nations, ceased development of offensive biological warfare several decades ago, there has not been a global commitment to do likewise. More worrisome are non-state adversaries who can pursue offensive biological warfare strategies beyond the purview and monitoring of responsible government; the efforts of the Aum Shinriko organization and the recent anthrax attack in the United States are cases in point.

The widespread application of modern molecular biology to create novel and targeted biological weapons, while possible, has not currently been experienced. If such weaponry were suspected to be available, serious policy and operational questions would arise as to how to deal with the potential risk. And, while this study was completed prior to the

September 11, 2001, series of events, the distribution of anthrax spores via the U.S. mail has now already stimulated the general debate over developing possible counters.

The use of biological weapons opens an entirely new battlefront, in that the target might not be restricted to military forces but could be the U.S. population at large. And while the effects of various biological agents vary in their speed from minutes to weeks, they can affect a large population well before effective remedies can be implemented, even if they are available.

The impact of biological attack on military operations is potentially devastating. The ability to deploy forces can be affected by consequences such as debilitated transportation systems and paralysis of ports—interfering with naval deployments, weapons shipments, and sustainment supplies.

As noted earlier, information is lacking as to precisely what biological warfare technologies and capabilities are being pursued around the world, but intelligence estimates postulate that more than a dozen nations possess or are pursuing offensive biological capabilities.

Smallpox is but one of may potential BW agents to which humans are vulnerable. While a known and well-understood agent with known vaccines for its various strains, the eradication of the disease in the early 1970s resulted in an international decision to terminate national vaccination programs. Even those previously vaccinated are now vulnerable, since vaccine effectiveness is estimated not to exceed 9 to 12 years. At present, vaccine supplies are insufficient to protect large populations, military or otherwise.

One simulation of a smallpox attack in the Tidewater Virginia area—where there is a broad concentration of key U.S. military installations of all the Services—concluded that, for the assumptions made, there could be 50 million deaths. Obviously, the assumptions for immunity, movement of infected personnel, and other key factors will drive the results of such simulations.

Defending Against Biological Weapons—The Operational and Technological Challenge

Developing a credible defense against and deterrence to the use of biological warfare agents requires a broad spectrum of capabilities. The demands on the S&T enterprise are significant and require a concerted, coordinated, and integrated investment portfolio much greater than the approximately $250 million per year the Department is spending today.

Defense against biological weapons is extremely difficult and requires a broad, systematic, and integrated approach.

A credible defense to deter biological warfare will require DoD to tap promptly and effectively into the vast and expanding expertise in biotechnology. Currently, DoD relationships with industry and academia are weak in this area, with limited expertise within the military. Further, the multi-billion-dollar research effort underway in the biotechnology community is primarily oriented towards lifesaving and commercial opportunities rather than DoD biowarfare concerns. Military biotechnology interests are focused on the following:

- ***Indications and warning***. Developing sensors and precursor identification; developing protection techniques and measures; and developing predictive indicators of activity for intelligence purposes.[11]
- ***Detection***. Standoff wide-area surveillance with multi-sensor, multi-dimensional data fusion; rapid agent identification and classification; new forensic techniques to determine, *inter alia*, attribution (signature of origin); expanded field diagnostic capabilities.
- ***Prediction***. Accurate, predictive dispersion modeling techniques supported by decision-making systems and field capabilities for rapid implementation, for civilian (such as, first responders) as well as military use.
- ***Characterization and Response***. Novel capabilities to understand and mitigate health and performance effects and neutralize toxicity; antidotes, vaccines, and therapeutics; ability to rapidly identify newly engineered agents; and ability to produce and prescribe effective countermeasures.
- ***Protection.*** Wide-spectrum pre-attack vaccines; collective and personal protection systems.
- ***Agent-Defeat Weapons***. The ability to attack rogue biological and chemical production and delivery targets; weapons capable of neutralizing facility and stored toxicity; ability to rapidly neutralize and destroy already-distributed agents over a wide area.

[11] Of particular interest would be standoff identification characterization. However, detection of biological agents from a standoff does not yet appear to be within technological reach and funding dedicated to such efforts should be targeted, controlled, and carefully assessed.

Vulnerabilities and Risks

The nature of advances in biotechnology and our understanding of fundamental structures and effects are increasing at a pace unimagined even a few years ago. Thus, while the current estimates ascribe a limited probability of the use of BW against the United States in the next decade, we could be surprised. Further, the nature of the agents used might be very different than expected and thus could defeat warning and response systems.

Today, the U.S. intelligence and public health systems have very modest capabilities in this area. As a result—as in the recent anthrax case in 2001—the first indication of BW agent use is likely to be identification of infected people, unless the agent used were extremely virulent. Detection is more likely to be "bottom up"—at the individual physician level—than to occur through a national detection system, which has not yet been organized or integrated.

Goals and Approach

Recent comprehensive reviews have identified major systemic problems with the current approach to biological warfare defense within DoD and these problems remain valid today. Currently, efforts are fragmented among multiple agencies. The relationship of DoD to non-DoD research is not well coordinated, and, most importantly, the magnitude of the effort is much too small. The Department lacks vision for action and lacks leadership and coherent organization. A major step forward can be made by putting someone in charge with the authority and resources to manage a comprehensive program in biological warfare defense.

Efforts for biological warfare defense must focus on two central goals—goals that are bold and aggressive, but represent the capability needed. They are to

- Enable U.S. forces and their support infrastructure to operate in the face of a biological warfare attack.
- Deter adversaries from using biological weapons.

Previous studies have proposed a number of initiatives that should be included in a comprehensive program for BW defense. In particular, the *1999 DSB Summer Study on 21st Century Defense Technology Strategies* proposed four major technology thrusts, which DoD should pursue.[12] One

[12] *The Defense Science Board 1999 Summer Study Task Force on 21st Century Defense Technology Strategies, Volume I (1999).*

of the four thrusts recommended by the study, BIOSHIELD, involves S&T investments on the order of $1.4B per year.

The S&T program proposed in that study included several dimensions: effective threat detection, effective threat response, and revolutionary treatment options. One element of an effective threat detection and response is the development of affordable sensor arrays that would allow blanket coverage of an area through wide dissemination. Another is development of a biosignature to assess a BW threat. The bio-signature concept would include genomics and proteomics profiles, biochemical fingerprints, and forensic attribution. Also important are decontamination and countermeasures such as rapid automated responses, new classes of decontaminants, and surface coatings to kill pathogens on contact.

Opportunities exist to use to use advances in biotechnology to develop revolutionary treatment options. Presymptomatic diagnosis of infection would enable early detection of the body defense reaction, allow rapid treatment for a better outcome, and enable optimal control of the spread of infection. Advanced vaccine technologies would allow expanded pathogen coverage and on-demand surge production of designer vaccines. The development of new drugs would provide immunity enhancement, a new broad spectrum of antibiotics, and pathogen grabbers.[13]

The Defense Science Board Task Force on Defense Against Biological Weapons examined the BW threat and in particular the implications for homeland defense.[14] A large-scale biological attack on the U.S. homeland would be devastating in its own right and would also have severe implications for DoD's ability to conduct its missions. Moreover, the attack of high-value military targets in the United States provides high-leverage asymmetric opportunities for an enemy, such as:

- Compromised U.S. force projection.
- Inevitable cross-infection of civilians involved in logistics support.
- Civilian impacts such as erosion of base services, panic, and hostility.

One of the urgent priorities identified in the 2000 study was the need to build a comprehensive, centralized database of bioagent fingerprints.

[13] Each of these initiatives is described in more technical detail in the *1999 Defense Science Board Summer Study on 21st Century Defense Technology Strategies, Volume II.*

[14] *Report of the Defense Science Board Task Force on Defense Against Biological Weapons: Leveraging Advances in Biotechnology and Medical Informatics to Improve Homeland Biodefense Capabilities*, 2000 Summer Study, Volume IV (Washington, DC: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics), October 2001.

These signatures would in turn enable the design of new diagnostics and testing technology and provide potential insights to guide strategies for drug and vaccine development. The study recommended creation of a data acquisition and information architecture for biodefense that would provide the following:

- A Bioagent Identification and Information Center, responsible for the collection, analysis, annotation and curation of a BIOPRINT database—a comprehensive inventory of molecular signatures (or "fingerprints") of the most medically common microbial infections and the top 50 biothreat agents. The center would:
  - Be laboratory-based.
  - Be responsible for sample collection, archiving and security.
  - Use genome sequencing and other profiling tools.
  - Probe designs for Z- and FZ-chips, to be used for rapid diagnostic testing to distinguish between conventional pathogens and bioagents.
  - Provide a secure repository of bioagents and profiling to limit open-source risks.
- A Bioagent Warning and Communication System that would provide a monitoring and alerting function for biodefense. It would include:
  - A computational network.
  - An alerting network for DoD bases and points of embarkment, TRICARE, reserve component, and the Center for Disease Control and other key civilian public health systems.
  - Advanced data-mining tools for epidemiological data.

Additionally, this study identified the need for creation of a New Joint Biodefense Organization.

The *Report of the Defense Science Board/Threat Reduction Advisory Committee Task Force on Biological Defense* is the most comprehensive of the previous studies. The recommendations of this study are extensive.[15] They include the following:

- Rank biological attack comparable to nuclear attack.

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[15] *Report of the Defense Science Board/Threat Reduction Advisory Committee Task Force on Biological Defense* (Washington D.C.: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics), June 2001.

- Enable military mission and thus strengthen civil defense.
- Implement a coherent strategy and put someone in charge.
- Anticipate a central role in civil defense.
- Build a strong science and technology base.
- Reengineer the role of intelligence and deterrence.
- Educate, game, red team, experiment, exercise, and train.

It is important to note that the 2001 DSB study concluded that the subject of biological defense is rich in opportunities for the DoD. Biological weapons have characteristic weaknesses—latency, sensitivity to environmental conditions, sensitivity to vaccines and medical care as countermeasures, and susceptibility to simple passive defenses.

The 2001 DSB study also concluded that there is much that can and should be done to both improve the response to and reduce the risk of biological weapons. The problem of BW defense is not "too hard" unless it includes the unrealistic objective of "zero casualties." Further, credible defenses and the means to attribute the sources of BW agents are tremendous deterrents to the use of biological weapons. Yet perceptions that the United States has both these capabilities are inaccurate.

The task force believes that a comprehensive program is essential. Many recommendations from previous studies are still valid. Key steps to developing an effective program include

- ***Establishing and designating an agency within DoD to manage all aspects of biological defense***. The need for someone in charge of this important area with authority, accountability and resources to direct *all* aspects of DoD's BW defense program is critical. Without this step, there is little hope for achieving the needed results. This effort deserves establishment of an organization comparable to the Missile Defense Agency.

- ***Implementing the recommendations for biological warfare defense of the 2001 Joint DSB/TRAC Task Force on Biological Defense***. This report describes the bulk of the activities that the Department of Defense needs to implement.

- ***Increasing the DoD S&T investment from $250 million per year to at least $1 billion per year***. A program of at least this magnitude is required to begin to adequately address this challenge.

- ***Implement the biological threat database and warning system recommendations of the 2000 DSB Task Force on Defense Against Biological Weapons*.**

2. Finding Difficult Targets

Unobscured, fixed military targets are relatively easy to detect and identify. However, moveable targets, concealed by camouflage or foliage, as well as targets in structures or underground, are currently extremely difficult to detect and identify using standoff sensors. Vehicles moving on the ground can be detected by ground moving target indicator (GMTI) radar such as Joint STARS, but it is difficult with current standoff sensors to identify them as military targets, particularly when they are obscured by weather.

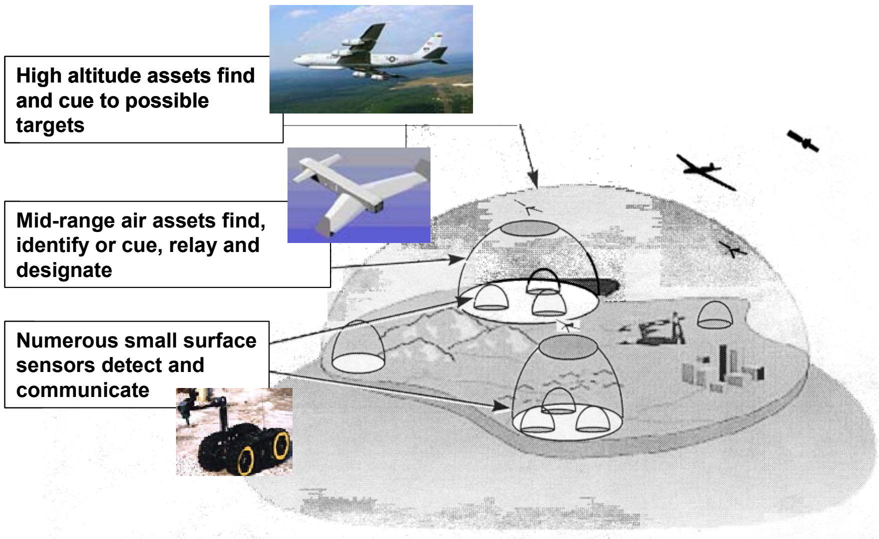
Recent experience in the Balkans and the Persian Gulf has demonstrated the difficulty of discriminating decoys from actual military targets. In Kosovo, for example, approximately 300 tank kills were claimed, but less than a dozen tank kills could be confirmed; in fact, many rounds hit only decoys. In the Persian Gulf, about 40 SCUDs were launched. Six thousand Allied sorties were flown against SCUD TELs, but no actual SCUD TELs were found and only about five decoys were destroyed.

The examples cited are situations where finding, identifying, and classifying targets has proven to be difficult. Technological and operational approaches to solve this problem are being pursued within DARPA as well as the four Services. DARPA is properly pursuing the particularly high-risk potential technological approaches, while the Services are more closely focused on nearer term solutions.

Concepts for Future Capabilities

Significantly increasing the capability to detect, identify, and discriminate valid targets is essential to U.S. military transformation. Multiple layers of intelligence, surveillance, and reconnaissance sensors are recommended in order to provide broad-area search both through long-range and shorter-range observation so that difficult targets may be detected, identified, and subsequently attacked. Since targets can be concealed in so many different ways, a multi-layered system employing many different sensor types will be more likely to successfully detect, identify, and discriminate difficult targets, and also be less sensitive to countermeasures, than any single sensor system in isolation. Figure 2-3 illustrates the elements of a layered ISR system.

Figure 2-3. Concept – Multiple Layers of Intelligence, Surveillance and Reconnaissance



Technology Requirements

The Department of Defense needs to establish a focused science and technology program to develop the elements of this multi-layer ISR system, to include high-altitude airborne, mid-to-low altitude airborne, and ground-based layers.

High-altitude Airborne Layer. In a multi-layered approach, high-altitude sensors would have the task of broad-area search for locations in which to employ the mid-to-low-altitude and ground-based sensors. The goal is to develop airborne radar capable of super range resolution, GMTI, and 3-dimensional imaging through foliage and into structures.

A three-part ultra high frequency (UHF) radar technology program is recommended for the high-altitude layer. All three parts of the program need to be started now, but demonstrations of these new capabilities will occur in phases due to the increasing difficulty of each. No science and technology programs currently exist to accomplish any of the following:

- Incorporate super-range resolution into UHF foliage-penetration radar without increasing interference with other military and civilian systems operating in the UHF portion of the spectrum.

- Add a GMTI mode to the UHF radar in order to detect vehicle movements under foliage and camouflage, as well as in the open.
- Add a three-dimensional, high-resolution imaging mode to the UHF radar to better separate targets under the trees from the treetops themselves in the radar return.

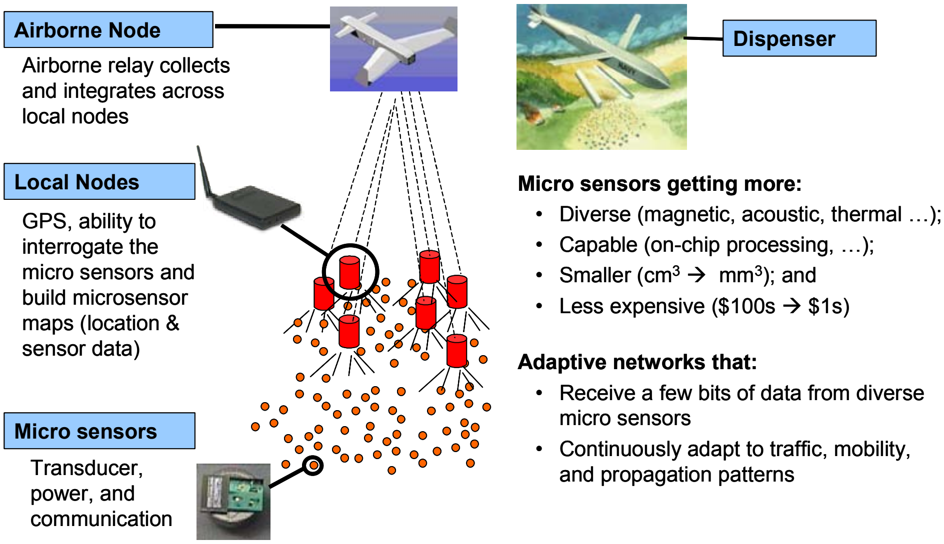
Mid-to-low-altitude Airborne Layer. Operating below the cloud layer, the mid-to-low-altitude airborne sensors would have the task of searching for targets, as well as investigating potential targets cued by the high-ltitude airborne sensors and other assets. A two-part technology program is recommended for this layer:

- Develop multi-spectral laser radar capable of three-dimensional imaging through camouflage and openings in foliage. This sensor would be hosted on a small, long-endurance unmanned aerial vehicle that is also equipped with a laser designator and communication capabilities up to the high-altitude layer and down to ground sensor networks.
- Develop a hovering and perching micro-air-vehicle with optical day and night vision. The vehicle should be able to approach within a few hundred meters of potential concealment locations to detect, identify, and discriminate difficult targets.

Ground-based Layer. Commercial micro sensors are becoming more diverse, more capable, smaller in size, and less expensive. Examples include radio frequency tags on store merchandise, accelerometers in automobile crash-safety systems, and audio amplifiers in hearing aids. This technology can be exploited to address the detection, identification, and discrimination of difficult military targets.

The concept is to dispense huge numbers of inexpensive micro sensors into areas of interest discovered by the high- and mid-to-low-altitude airborne sensors and other broad-area ISR assets. The layout also includes local control nodes that relay data from the micro sensors to the airborne nodes. There are no sensors on the local nodes (which are depicted as canisters in Figure 2-4 to symbolize work already done on the ARGUS program). The local and airborne nodes will autonomously form mesh networks with the microsensors. The mesh networks will use Internet Protocol-based routing algorithms and continuously adapt to changing traffic, mobility, and propagation patterns.

Figure 2-4. Layered ISR Approach



The ground-based sensor development program would begin with sensor devices of a single type (for example, a magnetometer or acoustic sensor) and expand over time to incorporate additional devices able to sense different phenomena. As additional sensor types were added to the network, various signatures would be systematically integrated and fused, compared to a template database, and used to predict, if not conclusively identify, the particular item of interest and properly classify whether it is a target of interest or not.

Vulnerabilities and Risks

Airborne Sensors. Super resolution, as well as UHF and three-dimensional imaging through foliage at UHF frequency ranges, has proven to be a difficult technical problem as is accurate navigation of a mini-UAV among trees or in dense urban terrain. Navigation would be further complicated by countermeasures such as nets or barriers, although, if these countermeasures were detected, flight altitudes could be adjusted without excessive mission degradation. The operational importance of this airborne sensing capability would lead to the development of countermeasures such as jammers and decoys. Landing and/or perching of mini-UAVs, while a highly desired operational capability, is currently difficult as well. Finally, the balance between autonomy and tele-operation for mini-UAV platforms is an area requiring additional study and resolution.

Ground-Based Microsensors. Ground-emplaced sensors need to be highly reliable with minimum false alarm rates. Making them so is difficult because of the wide range of stimuli that they must be assess and correctly categorize. One possibility to reduce false alarm rates is to explore the use of off-board processing for sophisticated assessments, either on airborne platforms or at a larger-capacity local ground node.

The discovery and removal of a local node is a vulnerability that could render a portion of an array inoperative (data exfiltration). Redundant local nodes that remain silent until queried by the airborne nodes and that can reconfigure their networks when a few nodes are removed may address this concern. Microsensors would be quite small, thereby making adversary detection more difficult but not impossible. Additional work needs to be done to minimize the probability of detection of such arrays and nodes; possible strategies include shielding transmissions, altering reporting cycles, and using power modes that are close to ambient noise levels. Even less expensive sensor and local node decoys could be added to the array to further complicate enemy removal of sufficient quantities to degrade the network.

The vitality and durability of a deployed sensor network is critically dependent on reliable and sustained power. Recharging from solar cells and introducing low-power "sleep" modes are possible approaches. Standoff delivery and effective deployment of the microsensors and local nodes is a technical challenge, but the Joint Standoff Weapon and Multi-Rocket Launch System should be investigated as possible dispensing mechanisms. Finally, until broad demand develops in the commercial market for micro sensors and associated nodes, the cost of these technologies may remain high and restricted to only the highest priority military applications.

Goals and Approach

The task force proposes a series of demonstration milestones occurring at 2, 5 and 10 years for both the airborne and ground-based layers. More specifically, for the airborne sensors, demonstration milestones would include the following:

- First demonstration, 2 years. UHF super range resolution using radar in test chamber and existing ground-based radar.
- Second demonstration, 5 years. Airborne foliage penetration GMTI radar with super range resolution mode finds moving and stationary vehicles under foliage; mini-

UAV day and night optical sensor and ladar identifies targets through openings in foliage; GPS coordinates with foliage penetration radar and identification from mini-UAV enables immediate targeting.

- Third demonstration, 10 years. Airborne foliage penetration GMTI and three-dimensional imaging radar; perching mini-UAV with optical sensor identifies fixed targets under foliage and targets in structures.

Specific demonstration milestones for ground-based micro sensors include the following:

- First demonstration, 2 years. Identify, discriminate, and track any vehicle in a one-kilometer square area in adverse weather conditions and/or under foliage; define countermeasure vulnerability; transmit near real-time to airborne relay(s).
- Second demonstration, 5 years. Identify, discriminate, and track people in addition to vehicles; increase area surveyed (increased challenge in data fusion); system should remain functional in active countermeasure environment.
- Third demonstration, 10 years. Integrate into common operating picture; inside buildings; underground facilities; mobile microsensors.

The phased demonstration approach will permit transition to acquisition programs in phases consistent with spiral development.[16] The task force recommends that DARPA manage the ground-based microsensor technology program because of its revolutionary nature. The Services may manage the airborne sensor programs, but it is essential that DDR&E have authority to harmonize the pieces so that an interoperable multi-layered ISR system can develop.

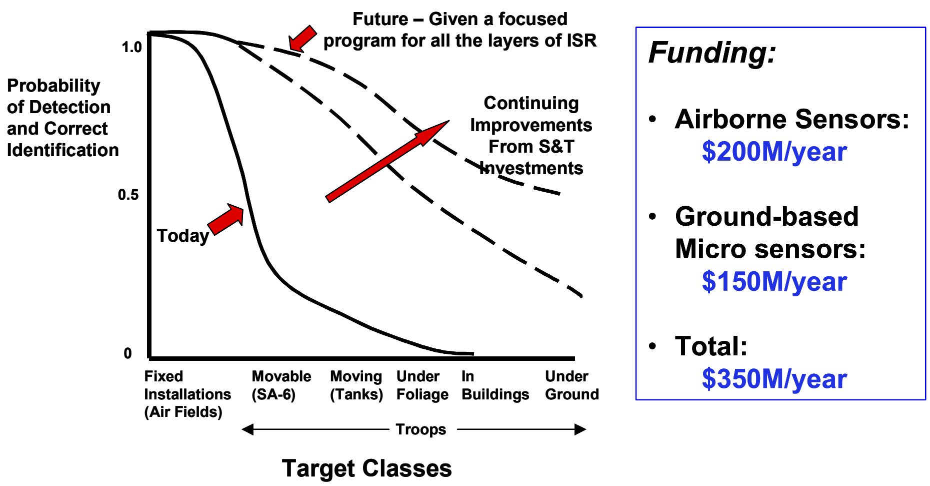
Figure 2-5 depicts notionally the potential for improved capability in the detection, identification, and classification of difficult targets. However, such progress is dependent upon results from ongoing and future scientific and technological efforts.

Taking a systematic approach to “finding difficult targets” and prioritizing S&T efforts across the various approaches—high-altitude airborne, mid-altitude airborne, and ground platforms—should bring about satisfactory solutions sooner. It is estimated that $200 million per year

[16] A discussion of spiral development can be found in Chapter 4.

will be required for the airborne sensor and platform technologies and $150 million per year will be required for the ground-based sensor technologies and the technology for their associated communications nodes.

Figure 2-5. Operational Improvement and Funding



3. Making Timely, Accurate Decisions

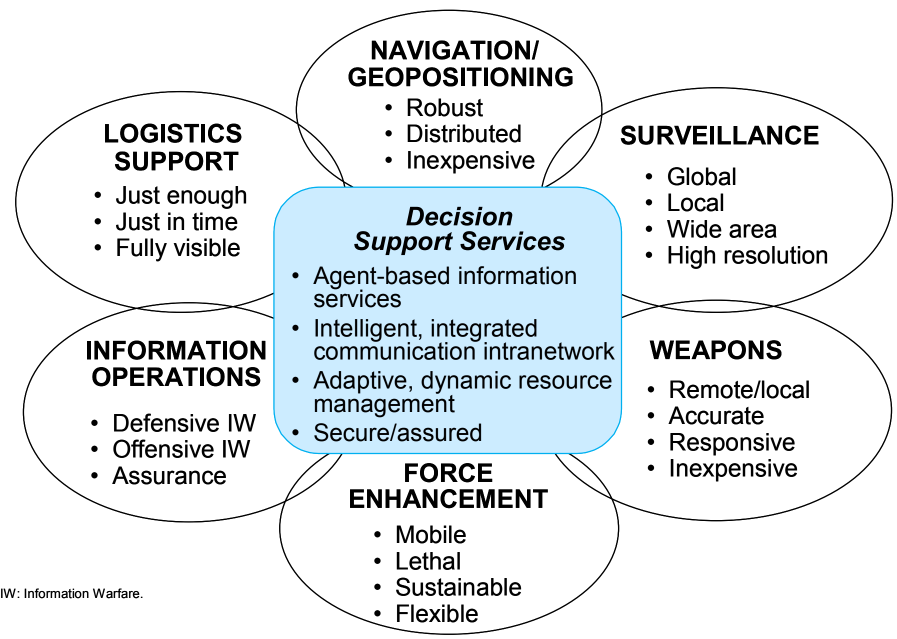
The many contingency operations undertaken by the U.S. military in the past decade highlight the fact that planning cycles for employing U.S. forces are too long to effectively conduct intended missions. The time required to collect and consolidate situational information, to analyze these data and develop a mission plan, and to gain approval for the plan, can result in a plan that no longer reflects reality when the mission is executed.

If U.S. forces are to be effective in the future, decision cycle time needs to be reduced from days or hours to minutes. Reducing decision cycle time will require exploiting information technologies and reengineering the command and control process and its culture. The first step is to develop and exploit information technology, which in turn will facilitate the needed process re-engineering.

Concepts for Future Capabilities

Timely, accurate decisions are the central element in all military functions and missions, as Figure 2-6 illustrates. An integrated decision-support system is needed to facilitate the decision-making process—a system composed of decision-support tools, intelligent information management, information fusion and dissemination, and integration of communications. The system should provide robust, assured information services to the warfighter very rapidly.

Figure 2-6. The Vision



IW: Information Warfare.

One concept for a decision-support system involves a multiple-layer construct where information is shared between layers. Entities—such as people, weapons platforms, sensors, or robots—would provide information to and use information from the system. The system would have the ability to dynamically adapt to meet the information needs of all entities. The multiple layers of the system would include:

- ***Decision-support tools*** capable of supporting a variety of interactions such as multi-party, on-line collaboration, faster than real-time course-of-action planning; and continuous machine-based planning.

- ***Information services*** that rely on intelligent software agents to provide automated information fusion, management, and dissemination services. Intelligent software agents would transform data into information to support unit operations and would proactively provide information to the user based on specific needs.
- ***Communication services*** that would take advantage of commercial technology and networks. This layer would be based on open-systems standards and protocols, with minimal use of Service- or function-unique hardware or software.

Technology Requirements

A great deal of available and evolving commercial information technology can be exploited as components for developing an integrated military decision-support system. Commercial information technology standards facilitate system interoperability and the technologies can provide improved decision response times. However, there are significant military enhancements needed to meet DoD operational requirements—capabilities such as self-healing and self-managed networking, anti-jam capabilities, low probability of intercept, and spread-spectrum waveforms.

Through a focused S&T program, it is possible for the Department to exploit the enormous private-sector investments in information technology. DoD should invest its information technology resources in three S&T areas: (1) decision support services, (2) information services, and (3) communication services.

Decision-Support Services. The technologies associated with decision-support services include generative planning, case-based reasoning, context-based information management, and coarse-grained dynamic parallel processing. The latter technology is intended to allow distributed parallel course-of-action generation. Additional technology challenges to be addressed include:

- Operating systems that provide coarse-grained, distributed, parallel processing between dispersed processing systems.
- Distributed algorithms that permit dynamic load leveling, adaptive computation, and self-management, to ensure graceful degradation at the point of service.
- Algorithms and protocols that tightly integrate distributed computational resources with transport infrastructure.

- Collaboration tools that support multi-party, real-time interaction.

Information Services. Information services are supported by intelligent software agents and related infrastructure. Intelligent *service application software agents* provide tailored data acquisition, processing, and fusion, and also generate and disseminate information to users. These agents deliver processed, synoptic information instead of volumes of data and images. The service application software agents collaborate to proactively recognize pertinent situation changes that may be of interest to the user. The agents replicate themselves as necessary for efficiency and to ensure that users are provided with continuous service.

Intelligent *application software agents* provide an array of functions appropriate to the user's mission and situation. The agents discover and integrate information from multiple, heterogeneous databases; broker information sharing between other agents; and negotiate with service agents to establish appropriate network and resource allocations. These agents are adaptive in that they profile user needs against direct user input, past user requirements, and an understanding of user mission, status, and intentions.

Intelligent software agent research and development is presently being pursued both in the private and public sectors and should be leveraged to achieve the capabilities described.

Communication Services. Communication services must transport information in a secure, reliable fashion and must be adaptive and self-healing. They include ground-based local area networks providing data and information services, airborne networks and processors to transport data and information services, and space segments to provide connectivity over widely dispersed areas. The following technology challenges must be met to develop integrated, scalable communication services. DoD has made a modest investment in these areas, but its efforts need to be expanded and focused on military-unique needs.

- Distributed algorithms and protocols that dynamically manage communication hardware to provide (1) real-time control of radio waveforms, link capacity, and network topology; (2) intra- and inter-network data routing; (3) distribution of network state information for adaptive, real-time self management; and (4) distribution of state information exchanged between transport and information-processing layers.

- Distributed inter-network management and control algorithms and protocols that permit topology configuration and balancing of loads across the network.
- Distributed algorithms and protocols that will adapt to meet dynamic quality-of-service requests made by the warfighter.

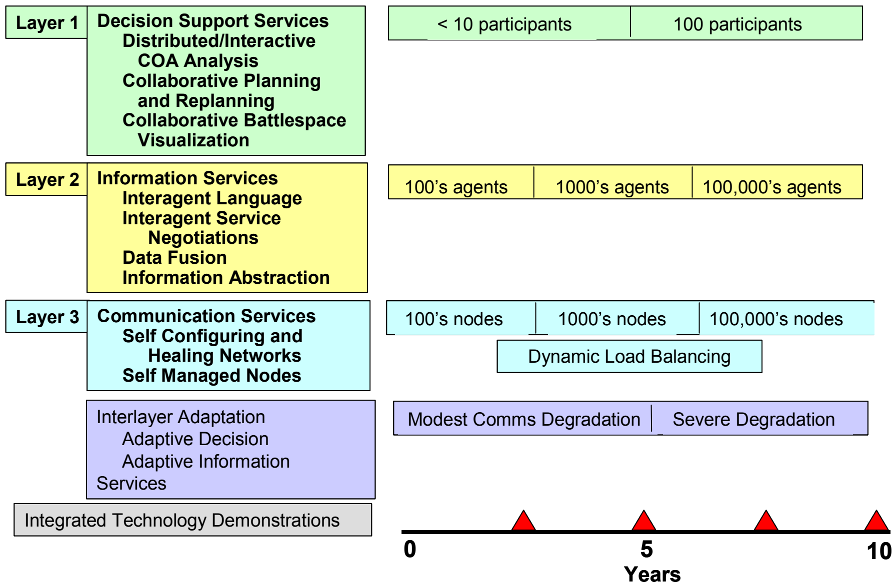
Goals and Approach

Figure 2-7 identifies the challenges that should be incorporated into a focused DoD S&T program to realize an operational decision-support system. The approach suggested would allow the capabilities in each layer to evolve over a 10-year period. For each layer, the technical challenges involve increasing the number of real or virtual entities that interact to support timely, accurate decision-making.

A series of advanced technology demonstrations are recommended every two and one-half years to integrate the capabilities in each layer. The demonstrations would be conducted against a specific set of operational metrics, based on the accomplishments in the earlier demonstration. As these metrics are demonstrated, the maturing technologies would ideally be transitioned into a baseline, integrated, operational, joint C4ISR system. The end result will be significant improvement in military operational capabilities, as the following metrics detail:

- Planning will not limit execution. Decision time will be reduced from hours or weeks to minutes.
- Ability to engage moving targets will increase significantly. For field artillery, it will be reduced from 30 minutes to time-of-flight plus seconds; for tactical air missions, from days to minutes.
- Decisions will be based on a more robust set of analyzed alternatives. The number of credible options analyzed will increase from one or two to tens.
- Decisions will be made more quickly than the opponent can counter—that is, within the opponent's decision cycle. Cycle time will be an order-of-magnitude faster than that of an opponent.
- Synchronization of joint and combined actions will occur, considering all relevant factors (including political and non-military). The collaboration community will increase from 8 to 10 entities to hundreds.

Figure 2-7. Time-Phased S&T Goals



This system should be established in the near term by leveraging commercial information technology and integrating existing DoD C4ISR systems. The agent for developing a baseline system should be Joint Forces Command, as suggested in numerous prior Defense Science Board studies. The S&T program to support the decision-support system would use the Joint Forces Command integrated-C4ISR baseline as the target for advanced technology transition and insertion. To manage the program, the many ongoing projects at DARPA and the Service laboratories and research centers should be aggregated under a single program executive director, who would focus additional S&T resources on developing the technologies needed to meet the vision described.

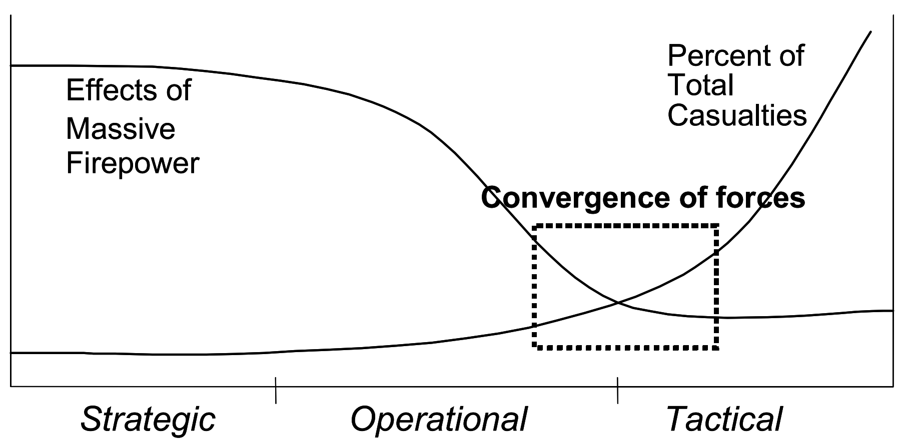
4. Enabling High-Risk Operations

Over the last century the United States has perfected its own unique style of warfare that relies heavily on firepower in support of maneuver. For example, when the Korean War began, U.S. forces used one artillery battalion to support each maneuver battalion; by the end of the war's first year, 14 artillery battalions supported each maneuver battalion. More

recently, the United States has relied heavily on air strikes as an additional form of firepower. In Desert Storm, 46,000 air-interdiction and close air-support air strikes were flown—many prior to the initiation of the ground campaign—in addition to 70,000 sorties of other types. Furthermore, the United States has sought to perfect standoff precision strikes as a way to use firepower without placing U.S. combat personnel in harm's way.

The impact of increased use of firepower on casualties is illustrated in Figure 2-8. The effects of massive firepower can be significant in the strategic and operational phases of war and then diminish at close-in tactical ranges. On the other hand, friendly casualties are relatively few during the strategic and operational phases of a conflict and increase dramatically as tactical combat closes to close range. The point where these two trend lines cross is termed the "point of convergence."

Figure 2-8. Relationship Between Firepower and Casualties



Over the last decade, adversaries have sought through various methods to force U.S. forces into close combat—avoiding the effects of U.S. firepower and taking advantage of the potential for higher U.S. casualties. (Over the past one hundred years, 97 percent of all casualties have been in close combat, with 85 percent in the infantry.) The United States will continue to face close-combat situations when trying to achieve particular military objectives. As a result, new approaches—such as the use of unmanned systems—are needed to reduce risk to U.S. forces.

Future Operational Concepts

Unmanned systems offer the potential to regain the initiative in close-in combat by forcing the adversary to operate at a higher operational tempo than he can manage. Unmanned systems can operate in conjunction with manned forces while greatly reducing the exposure of manned forces and can also be used for some high-risk tasks in the operational phase of a conflict. Additional advantages could include

- Potential for a true "train as you fight" process.
- Simulator training that is the same as combat operations.
- Greater reach-back capability for remote war fighting.
- Lower cost of training, operations and maintenance, and logistics.
- Long endurance and wider dynamic range.
- Enhanced survivability at greater ranges of temperature, pressure, g-load, and altitude.
- Ability to conduct "one way" missions.
- Support and facilitation of team and joint operations.
- Greater multi-mission, multi-sensor potential.

The use of unmanned systems in combat has been limited. The United States used unmanned aerial vehicles to a very limited extent during the Vietnam War and subsequent combat engagements, primarily for reconnaissance and signals-collection purposes. Their expanded use in recent years reflects not only the utility of improved technology but also increased acceptance of such capabilities to reduce risk to manned systems as well as to relegate more mundane and routine tasks to automated systems, as Figure 2-9 suggests. Newer approaches, such as the use of robotic systems to perform these and other tasks, need further conceptualization and testing.

Use of unmanned aerial vehicles, while still in its infancy, has largely been accepted as a useful approach that requires expansion and further exploitation. Operationally useful unmanned ground vehicles, however, are not yet in widespread use. This fact is due to the difficult technical challenge of coping with the much more complex ground environment—possibly including poor weather, short lines-of-sight, and complex and urban terrain—in and around buildings, trees, ditches, standing water, and rubble, for example—and the more complex and diverse tactical situations of ground operations. All of these factors combine to place constraints and demands on the performance attributes such systems must possess. For

unmanned systems (both aerial and ground) to be useful in supporting infantry or carrying out infantry tasks, an array of technologies must be advanced and integrated.

Figure 2-9. Unmanned Systems

Broadly speaking, the technical advances required are in behaviors, mobility, power, miniaturization of sensors and processing, and lethality of small weapons. But unmanned ground systems must possess two other important attributes besides being functional themselves. First, they must be integrated into the overall set of infantry systems, including being controlled by humans when appropriate. Second, they must carry out their tasks within the constraints imposed by the rules of engagement—and these can sometimes be quite restrictive and complex.

Technology Requirements

While few systems have actually been fielded, technologies related to unmanned vehicles have advanced significantly over the past several decades. Many of these technologies can be integrated into an accelerated, focused program leading to a meaningful ground operational capability.

Key technological needs include

- Assured wideband communications providing near real-time updates to operators.
- Development of self-learning, reasoning, and behavioral algorithms.
- Integration of multi-int sensors with a robotic strike platform.
- Neural modeling.
- Traditional wheeled vehicle tracked to organic mimicking walking and crawling vehicles.
- Sensory exploitation and interaction with robotic control architectures.
- Navigation and target detection sensor abstractions.

Goals and Approach

To develop the needed technologies, a multi-phased, 10-year S&T program is recommended. The program would be structured into two technically aggressive, successive five-year demonstration programs. Each of these programs would culminate in an advanced technology demonstration in which several lethal, highly mobile, reasoning robots would be demonstrated in complex and realistic operational environments.

The goal of the overall program would be to develop a company-sized force, of manned and unmanned systems, which would demonstrate a clearing operation in an occupied urban block. The unmanned force would be remotely directed to clear and secure buildings and streets, detain and secure a segment of the population, and provide force protection. The objective would be to demonstrate the ability of the unmanned systems in

- Integration with human forces.
- Self-protection.
- Verification of hostile forces and non-combatants.
- Engagement of resisting hostile forces.
- Controlling and guiding non-combatants to the manned force.
- Conforming to rules of engagement.

Phase I of the program would involve demonstration of semi-autonomous systems in the 2003 to 2008 timeframe, at a cost of $150 million annually. The concept would be to conduct "platoon" sided, urban assault in a free-fire zone. The Phase II demonstration, occurring from 2008 to 2012 at a cost of $100 million annually, would involve conduct of a company-sized operation. This part of the program would expand both the size and the operational requirements of the unmanned force.

5. Missile Defense

Deployed U.S. military forces and the U.S. homeland face a genuine threat from missile attack. Types of missile threats include surface-to-air, air-to-air, and surface-to-surface missiles as well as long-range cruise missiles and ballistic missiles. These missiles could be launched against deployed U.S. forces and/or the homeland to attack the full array of U.S. personnel and assets, including not only U.S. domestic and overseas fixed installations, air and seaports, command and communication facilities, and logistics centers but also U.S. urban centers, transportation networks, industrial complexes and other facilities of value.

The United States has made a major investment in national and theater ballistic missile defense over the past two decades. This effort has yet to yield a deployable system, although several systems seem to be near deployment today. The difficulties associated with missile defense are well known. Current systems depend on uncertain capability to discriminate real targets from decoys and debris as well as the challenging technique of "hit to kill." They also employ either very sophisticated and expensive ground-based interceptors or relatively inefficient airborne or ground-based chemical lasers.

Existing approaches cannot adequately defend against the threat of cruise and ballistic missiles at all ranges. The cost of effective defenses, the horizon limitations of ground-based systems, and the difficulty of achieving confidence in discrimination approaches all suggest that a better solution needs to be found.

One technology with the potential to address the limitations of systems currently in development is the use of high-power electrically powered lasers. These devices could be particularly applicable to theater missile defense against relatively short-range threats.

6. Affordable Precision Munitions

Recent warfighting experience highlights the importance of precision and low-collateral-damage engagement. This phenomenon has evolved since Desert Storm and today represents one of the most demanding requirements placed on the U.S. warfighting infrastructure. Precision weapons are often difficult to handle, difficult to employ, and costly. Further, many of the target-designation and guidance systems employed have inherent limitations, and many are susceptible to jamming or countermeasures. Today's systems also lack all-weather capability, which severely limits utility. Moreover, the effects are often not scalable. Existing precision weapons are generally delivered only by air, and other ground and naval options are needed.

Concepts for Future Capabilities

The trend toward precision and effects-based operations will likely continue. Extended-range engagement, employing precision munitions, will be a preferred means in all warfare regimes. Precision will need to be available to tactical forces—in the air, on land, and at sea. Precision munitions will replace unguided munitions for almost all targets. In the future, selective warhead effects will be needed, so that the effects can be tailored to the characteristics of the target. These systems will need to be capable of delivery very close to U.S. forces or to non-combatants. Finally, they will need to employ cost-effective munitions that can be used to engage discrete targets down to individual enemy soldiers

Technology Requirements

The Department of Defense has developed precision systems, thus far, with an emphasis on performance over cost. New technology is needed to make these systems more affordable. Technological opportunities include

- New energetic materials for propulsion and warheads.
- Multi-mode warhead technologies to reduce the need for multiple weapon types.
- Jam-proof, redundant, autonomous guidance.
- Adaptive, post-launch target insertion.
- Lower cost, which facilitates large-scale production.

In developing new approaches, it will be possible to leverage commercial technology such as inexpensive commercial sensor materials,

low-cost, producible, micro-electro-mechanical technology for guidance, and nanomaterials for very lightweight structures.

Vulnerability and Risk

The availability of rapidly developing commercial technology and adaptability of potential adversaries creates unknown but inevitable opportunities for unexpected counters to existing U.S. precision means. The only response is continuous improvements to weaponry.

A number of potential vulnerabilities exist. Total reliance on precision can lead to large-sector failures—the result of enemy counters such as GPS jamming. Unforeseen countermeasures can eliminate the effectiveness of some weapons. Sensor and communication network and information infrastructures provide an opportunity for indirect attacks on the precision weapon architecture. In the future, adversaries may present a proliferation of credible targets beyond the capacity of the precision weapon inventory. Finally, the time to engage—involving processing, prioritizing, time of flight, number of "launchers," and rate of engagement—limits the number of engagements possible prior to closure of forces.

Goals and Approach

Tremendous benefit can be realized through modest investment to leverage military and commercial efforts. It is important to focus on design for affordability, ease of handling, and employment. A recommended program should include:

- Implementing the recommendations of the 2001 Defense Science Board Summer Study on Precision Targeting.
- Structuring a tri-Service technology program to reduce the cost and improve the flexibility, adaptability, and robustness of precision munitions.
- Pursuing a mix of military and commercial technologies as described above.
- Developing a suite of technologies available for integration into munitions as soon as available.

The annual funding required for such an effort is estimated at $50 million.

7. ENHANCED HUMAN PERFORMANCE

Joint Vision 2020 envisions new and more demanding missions achieved with highly sophisticated equipment. Technology will equip the armed forces with weapons systems capable of sustained, round-the-clock operations. The people who man these systems must be able to keep pace. Military tasks will increase in complexity. It is estimated that an increasing number of the Army's basic tasks for its Future Combat Systems will be very complex. These tasks will have to be accomplished by fewer people with far less supervision in tomorrow's extended battlefield. There will also be new tasks to accomplish. Some of the non-traditional special operations missions will require non-traditional skills for success. Despite these increasing demands, future recruits will be much like those of today in terms of skill, knowledge, and attributes.

The armed forces are expected to continue using current instruments to measure skills, knowledge, and attributes—and many of these tools are very crude. These instruments are not fine-tuned to measure some of the requirements for information-age weapons systems. They also do not adequately measure the skills, knowledge, and attributes of people with less advantageous educational backgrounds and who do not speak English as a principal language. DoD definitely needs more sophisticated and technologically advanced testing instruments and training capabilities to properly measure, assign, and prepare people.

The Department also needs to use science and technology to help improve performance and to enhance the ability of humans to operate effectively on the battlefield. Acceptable methods of sustaining peak performance, fighting fatigue, coping with little or no sleep, and coping with stress must be developed.

Concepts for Future Capabilities

Science and technology can assist the DoD in identifying and preparing superior fighting men and women by identifying and measuring the skills, knowledge, and attributes that are essential for success on the battlefield. This task is not equivalent to selecting world-class athletes, but there are similarities. Physical strength and endurance will be required for many tasks but not for all. Personality profiles can identify those who will be successful on an unstructured battlefield. Certainly confidence, functional intelligence, and an indomitable will characterize many successful warriors. Such traits can be measured, but not with today's tools.

Technology can be used to minimize combat fatigue and the requirements for sleep, minimize the adverse effects of stress, and better tolerate physical demands and heat. Heightened visual acuity, enhanced night vision, widened hearing thresholds, and an expanded range of detectible audio frequencies will improve situational awareness. Decision-making aids and personal virtual assistants will enhance cognitive skills. With more capable operators, U.S. weapons systems can be used to the limit of their capability parameters and designed in a manner consistent with improved human performance.

Technological Opportunities

Modern medical science has developed remarkable new techniques to restore disabled functionality. Sports medicine has produced superior athletes. Many of these same approaches can be used to enhance normal functionality. Promising new techniques include cognitive psychology, cell signaling and regulation, implants, artificial organs, and pharmacology. These technologies can lead to greater performance and reduced casualties.

The task force believes that these techniques will enable the United States to field more effective humans with increased strength, reflexes, alertness, memory, sensory perceptions, cognitive abilities, and resistance to temperature extremes and motion sickness. Science and technology will help to decrease and regulate sleep requirements, caloric intake, fatigue, sensitivity to pain and counter productive stress reactions, and serious injuries.

One simple, but remarkable opportunity has involved cooling the core body temperature in order to dramatically increase endurance.[17] In one study, regular cooling of the core body resulted in a 200 percent increase in the number of pull-ups performed per day over a series of days versus an 80 percent increase achieved under normal conditions. This research provides considerable insight into ways of increasing human physical strength that could have specific battlefield applications. Given the high payoff for using such techniques with special operations forces, for example, the task force supports further research in this area at an estimated $30 million per year.

Vulnerability and Risk

Initiatives to enhance human performance have a mixed history of success and a perception by the general public and in the Congress of

[17] Further detail on this example can be found in Chapter III.

secretive and abusive applications. Invasive procedures such as implants and administration of drugs are particularly sensitive subjects. The DoD should limit its efforts to safe, reversible techniques for enhancing human performance that are generally acceptable to our society.

Care must be taken to be both conservative and open in pursuing these initiatives. Unforeseen consequences must be anticipated and addressed. Even though this area is sensitive and subject to understandable scrutiny, it should be investigated in order to enhance military capabilities. The United States should also be concerned that potential opponents will exploit science to create weapons systems and superior performing people to oppose U.S. forces.

Goals and Approach

For the near term, S&T initiatives for enhancing human performance should continue to focus on adding hardware to enhance the performance of humans. The Services have programs that are addressing brain/machine interface, better infrared goggles, hearing enhancers, sonar and echolocation capabilities, and health monitors.

In the long term, DoD should approach physiological and psychological enhancements. The possibilities include a wide range of areas to include cochlear implants, retinal implants, implanted micromonitor and microtracking devices such as virtual retinal displays and in-ear language translators, supplements to food and drink, and advanced skills, knowledge, and attitudes assessment and selection tools.

8. Rapid Deployment

The U.S. military is often required to deliver large amounts of equipment to distant places to support the national policy of carrying the fight to the enemy. Airlift is used to carry the materiel needed early in a mission, if it is light enough and can fit within the various transport aircraft. The majority of needed materiel is carried by sealift. Approximately 95 percent of the materiel used in Desert Shield and Desert Storm arrived by sea and at a pace that necessitated a lot of time to build up the force. Even a decade later, current air and sealift transport cannot move large forces and materiel to a distant crisis in less than weeks or months—although limited forces can be deployed more quickly.

The vision for the future assumes that access needs to be achieved very quickly and that forces and materiel need to be assembled and supported quickly. This speed can be accomplished by a combined approach of: (a)

increasing the speed of ships that carry the heavy and bulky materiel, (b) increasing the volume and weight that can be carried by airlift, and (c) developing ground-force systems that are sufficiently lightweight to be carried by aircraft. Improvements in all of these areas should be pursued.

Concepts for Future Capabilities

Future concepts for more rapid deployment and employment capabilities involve three potential thrusts.

Fast Sealift. Fast-sealift concepts can be supported by a dual approach of reducing drag by various means and increasing propulsive efficiency. The former results in much higher speed at today's thermodynamic efficiency (resulting in an increase in range), the latter in additional range or carrying capacity.

High-Capacity Airlift. Airlift concepts trade the difficulties of "logistics over the shore" with the need for airports in which to land and off-load. Lighter-than-air aircraft have an advantage in that the requirement for field terminal facilities is minimal and close to the front (though visible and potentially vulnerable). However, these aircraft are dependent on low wind speeds for tactical off-loading and carry limited payloads (less than 5-10 percent of that carried by an average ship). Other airlift options include developing a large fleet of new short takeoff and land tactical aircraft.

Light-Weight Force. The Army and DARPA are pursuing a major initiative to develop the Future Combat System (FCS) to drastically reduce the weight the Army must carry to the front. C-130s are the mainstay of DoD's tactical lift, and the FCS is being designed to use the long remaining life of these aircraft.

Technology Requirements

Sealift Technology. Fast sealift will be possible when effective lift-to-drag is substantially improved. Ship drag is primarily made up of two components—wave drag and friction drag. Wave drag is entirely due to the form of the hull and in particular due to the beam of the ship. Friction drag is directly related to turbulence, and therefore not easily controlled. Both must be addressed, and in both cases improved propulsion is part of the solution.

Eliminating wave drag requires that the ship have minimum interaction with the surface of the ocean, which implies either deeply submerged buoyancy connected to a boxy hull by thin struts (as in Small Waterplane Area Twin Hull ships) or deeply submerged lift-generating

surfaces connected to the hull by thin struts (as in hydrofoils). Other configurations are being explored as well. Reduction of friction drag is possible by lubricating the interface between the hull and the water. Lubricants that show promise include microbubbles, polymers (some specially designed for the purpose), and supercavitation.

If, in addition, using higher energy density fuels, such as hydrogen, and more efficient thermal energy conversion methods, such as fuel cells, increases thermodynamic efficiency, additional range or payload becomes available.

Airlift Technology. Delivering materiel near the front requires the ability to use undeveloped terrain, which translates into exploitation of short-takeoff-and-landing, tilt-wing, and tilt-rotor technologies. For strategic airlift high-capacity designs have been studied to the point where additional S&T investment is required to provide proof-of-principle demonstrations. Partially buoyant concepts offer the potential to provide high-capacity airlift without the requirement of large, fixed runways. While these technologies have been developed to some extent, additional performance is likely to be required. Industry has developed design concepts that can meet future needs, but S&T funding is needed to demonstrate the practicality and utility of these concepts.

Ground-Force Technology. Technologies required to develop a light-weight force include: advanced, integrated C4ISR systems and applications; unmanned systems; integrated survivability suites; extended-range, precision munitions technology; and hybrid electric propulsion. The Army is moving very aggressively to field the first operational generation of these technologies in the FCS program.

Vulnerabilities and Risks

Preparing a access denial capability is in some ways easier than building a capability to attack. An adversary can concentrate resources to build such a capability. In addition, the speed with which technology may proliferate makes it possible that systems, concepts, and technologies that deny access can outpace the counterpart developments in deployment of offensive capability. Commercially available technologies, with military application, may be used by smaller nations to develop access denial capabilities.

Other challenges are associated with developing more rapid deployment capabilities. First, sealift must be complemented by rapid loading and off-loading technology, including over-the-beach capabilities. The cost of airlift could be prohibitive. The survivability goals for light

ground forces are challenging and may not be achieved as desired, or may be easily countered by responsive threats.

Goals and Approach

Fast Sealift. Hulls designed for wave-drag reduction need to be explored in a consistent way that includes known forms and hopefully provides analytical avenues to extend the range of options. New forms identified by this process need to be tested, probably in traditional ways at existing facilities.

The goal for friction drag is an order-of-magnitude reduction. The least expensive way to obtain the capability to perform the required tests is to refurbish the Detroit Dam facility, which is estimated to cost approximately $10 million. The Office of Naval Research has declared strong interest in supporting research at such a facility at about $3 to 4 million per year. In addition, several universities with interest in fluid mechanics have offered to prepare work packages for sponsored research. An investment of $3 to 4 million per year for four to five years after the facility becomes available will support great advances in this area.

Advanced Airlift. Major aerospace contractors have developed designs for both advanced tactical and strategic transport. While innovative, these designs are not long-term technologies. A decision to pursue either one or both of these designs depends on a consensus in the Department of Defense about the need for and priority of advanced tactical and strategic airlift.

Lightweight Force. FCS is a multi-faceted program, which the Army seems to be fully committed to and investing in heavily. Continued S&T investments beyond the first generation of FCS will be needed to maintain its performance and address threats to the survivability of light vehicles.

9. Global Effects

The global strategic environment has changed dramatically—a result of globalization, the information revolution, revolutionary technological developments, the decline of nation state power, and proliferation of asymmetric threats. To deal with this altered world, a new conceptual approach called "global effects" has been developed. The implementing process for this new approach is "effects-based operations," which focuses on planning, assessing, and executing military activities based on the effects that they produce rather than the destruction of individual targets or even the objectives they deal with.

This new approach is necessary in order to deal more effectively with the diverse set of threats facing the United States. Such threats are frequently asymmetric and covert and are difficult to trace or deter. As the tragic events of September 11 demonstrated, the United States itself is a vulnerable target for terrorist attacks. The U.S. military must now provide needed capabilities to defend the homeland and to maintain forward presence, and readiness to conduct power projection missions. The general view is that the conditions of today will continue to be characterized by limited wars fought with limited means for limited ends, with low risk of military escalation in circumstances where the rules of engagement are often uniquely crafted.

To confront asymmetric threats, the United States will increasingly rely on the rapid and precise application of power through a combination of military and non-military (such as diplomatic or economic) means. Objectives will be broad, ranging from manipulating knowledge and perception to the traditional task of seizing territory. Warfighters will increasingly rely on agile, flexible, and decisive use of force, rather than overwhelming massing of forces. Widely dispersed combatants will look to leverage the unprecedented "instantaneity" of modern war to seize the initiative and better inflict strategic and operational-level surprise.

An additional aspect of the new situation to appreciate is that asymmetric situations can arise quickly, requiring almost immediate response anywhere on the globe. The United States must be able to act promptly in order to quickly set the conditions of a conflict before they become too difficult to change, thereby risking the situation developing into a protracted, indecisive first phase of a contingency. Such responsiveness not only implies global reach but also global sustainability to bring about prompt fulfillment of U.S. political objectives and expectations.

The Concept

Global effects—the ability to defeat any adversary using effects-based operations, anywhere around the globe, at any point on the spectrum of conflict—will be crucial to warfighting success in this environment. Three key capabilities are essential to producing global effects: the ability of air and space forces to operate routinely and simultaneously across strategic, operational, and tactical levels of warfighting; the ability to use decisive force; and information dominance. Global effects are key to achieving the full-spectrum dominance articulated in Joint Vision 2020.

The “effects-based operations” process requires special tools and task-organized units that take as input the “Commander’s Intent” and produce

output-oriented, effects-based courses of action to achieve the desired military effects for a given mission, including quantified estimates as to the likelihood of achieving the desired effects for each course of action. The process is also dynamic, continuing to assess and reassess the courses of action during planning and execution to optimize the desired military outcome.

Linking New Concepts to Future Capabilities

To be successful, the global-effects approach requires continued development of joint air and space capabilities. Joint air and space power provides a perspective that is global, regional, and local in scope providing rapid target recognition and re-strike capabilities in all operating regimes. The desired objective is simultaneous execution of joint air and space power at the strategic, operational, and tactical levels of warfighting. The net intent is to achieve the outcome desired by overwhelming the opponent with multiple attacks against hundreds of targets at once—limiting the freedom of action of that opponent.

It will be necessary to develop new operational, organizational, and technological concepts, including Joint/Combined Air and Space Operations Centers configured and equipped to function as complete command-and-control weapon systems. The Joint/Combined Air Operations Center will direct air campaigns and integrate air and space operations across the spectrum of conflict. Leveraging these capabilities, joint/combined air and space assets can be seamlessly integrated, ensuring information superiority throughout the battlespace—crucial to achieving global effects—and thereby providing U.S. forces with a distinct advantage at any level of warfare.

Capabilities to achieve information superiority include improved data collection, analysis, and fusion; real-time communications (to include bypass capabilities direct to "shooters"); remote sensing capabilities that are networked and internetted for real-time exploitation; time-critical target acquisition; effective fire control; and improved timing and guidance functions for military systems. Through horizontal integration, advanced surveillance and information management technologies will give warfighters vastly improved local, regional and theater situational awareness as well as the ability to act decisively in real time. The eventual goal is the ability to find, fix, track, and potentially attack any target on the surface of the planet at any time of the day. Flexible targeting will permit air- and space-based systems to change their target vectors en route through space-based communications.

A natural corollary of information superiority is a materially improved capability to provide integrated intelligence to users commensurate with their time line demands. In this integrated conceptual context, all-weather intelligence, surveillance, and reconnaissance assets will monitor adversary actions; identify, locate, and track targets and threats; and appropriately task, process, exploit, and disseminate the required intelligence directly to users, including "shooters" where appropriate. Accurate and timely intelligence will ensure "predictive battlespace awareness," by providing decision makers with actionable information that gives them a proactive awareness of unfolding battlespace events including likely adversary courses of action.

One emerging near-term expectation is much greater use of low-observable and standoff systems to provide access to high-risk or denied battlespace in order to identify and defeat adversary capabilities. These assets will complement other joint air- and space-power assets and must be able to rapidly deploy directly from CONUS and forward-based home stations with little or no warning. They must be able to operate as an integral element in the overall information collection, assessment, and distribution system.

Technology Requirements

Successful implementation of the "global effects" concept will depend heavily on advancements in technology, particularly seamless integration of information and intelligence inputs as well as maintenance of operational confidence in the quality, accuracy and timeliness of the various products and capabilities provided to leaders, planners and operators. Key among the needed technology advancements are

- Incorporating and integrating new sensor technology into the Global Information Grid.
- Determining the best "mix" and distribution of complementary sensors among ground, sea, air, and space platforms.
- Maintaining "trust" in the information infrastructure, the Global Information Grid, by insuring it's reliable protection against intrusion, exploitation, corruption or disruption
- Operating Joint/Combined Air and Space Operations Centers as weapon systems.

Sensor Technology and Mix. Advances in sensor technology will enable U.S. forces to further exploit and manage the battlespace. In the

future, information supplied by space-based radar and multispectral imagery sensors will need to be optimally incorporated and integrated into the existing constellation of ground-, sea-, air- and space-based C4ISR assets. Data from new and existing sources and sensors must be vetted and seamlessly merged into information provided to decision-makers, at all levels, in near real time. These new information resources and sensors also have to be evaluated to determine whether their best contribution to predictive battlespace awareness is from ground, air, or space platforms, or a combination of platforms. U.S. forces should then be able to maximize global effects operations while minimizing resource vulnerabilities.

Information Protection. One of the most pressing issues in the Information Age is protecting, managing, and ensuring the integrity of information while at the same time correlating, fusing, managing, and turning information into reliable, actionable knowledge. This challenge includes finding workable and secure means to readily share battlespace information with allies and coalition partners, some of whom may become adversaries in the next conflict. To this end, the Services must carefully balance the need to share information with the need to protect it.

Command and Control: A Weapons System. The ability to operate Joint/Combined Air Operations Centers as command and control “weapon systems” will be difficult to achieve. The many pieces to this weapon system need to be fully integrated to work most effectively in support of global-effects operations. Currently information comes from legacy, “stove-piped” systems that need to be networked together. Future forces will rely on seamless information sharing among joint, service, and coalition systems. In the interim, the information technology hardware, software, and corresponding processes that make up the Global Information Grid will continue to evolve and change.

By leveraging new operational, organizational, and technological concepts to better exploit a global-effects strategy, U.S. forces will be able to improve their unique asymmetric advantage and dominate the changing global security environment.

S&T AND OPERATIONAL INTERFACE

Throughout the process of identifying high-priority military needs, the need to strengthen the relationship between the operational and S&T

communities became increasingly apparent to the task force. Today, the relationship between these two communities is far from satisfactory. They lack a strong, continuous, two-way exchange of ideas and information on technical constraints and relative operational priorities. Because of the accelerated pace of technology, operators must increasingly rely on others for technology insights. Technologists must listen carefully to feedback about real operational insights and priorities. The level of dialogue on technical opportunity and operational potential is currently inadequate.

To the extent that communication does exist, it suffers in a number of ways. On the one hand, the operational community tends to follow a policy of benign neglect toward S&T investment until specific capabilities are needed. Then the operational community tends to pose arbitrary and often unrealistic packages of performance objectives—as though technology is available "on demand" without regard to the cost or realism of the technical parameters. On the other hand, the existing S&T community tends to take a broad, distributed approach to resource allocation, with vested interests "dividing up the pie" over the spectrum of technologies and applications. The result is institutional inertia in the pursuit of technology—and in the allocation of technology investments—without careful reference to its cost benefit or to its operational utility and priority.

Neither situation is beneficial to DoD. Both lead to inefficient resource allocation and inertia in the system. They also result in delays in the efficient transition of valuable technology to the warfighter. Joint needs in particular are short-changed because of the lack of a strong joint voice in S&T investment allocation process.

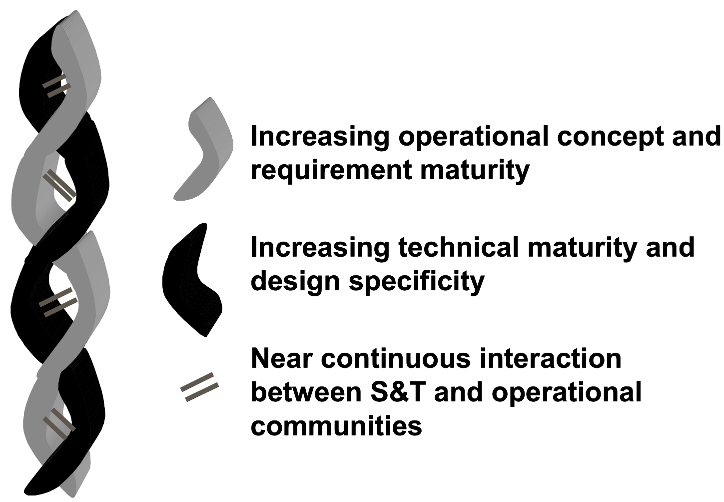
These observations are not directed at any particular organization or individual. While the Department does not suffer from these problems across-the-board, they are sufficiently widespread to warrant serious consideration and corrective action. Human nature, organizational structures, and differing perspectives essentially explain the current relationship between the S&T and operational communities. The issue is not blame; it is creating a more effective system.

IMPROVING OPERATIONAL AND S&T INTERACTION

A conceptual solution, consistent with current management approaches in the formal acquisition process, could help to improve deficiencies in the S&T system. Figure 2-10—depicting the double helix—portrays the type of collaborative, interactive model for prioritizing S&T research and

investment that is both desirable and possible. The concept starts with the assumption that both the operational and S&T communities have much to learn. They have much to learn about technology and about operations and about the interactions of the two. These learning processes are not independent, but are interwoven as the figure portrays. As both communities learn they inform each other and accelerate the entire process. At appropriate points, based on technical opportunity and operational insights, technology is transitioned to development and production.

Figure 2-10. The Double Helix Model



The dialogue and relationship imagined in this model demonstrate both dependency and support between the two communities. The model offers a structure that is stronger and allows operation and technical concepts to mature more quickly because of a higher degree of interaction and information exchange. If implemented, this approach could make a significant difference in the productivity of the Department's S&T effort.

For the S&T community to respond intelligently to user needs and to understand the users' perspective and priorities, and for the user community to intelligently consider and respond to the limitations and opportunities S&T can provide, there needs to be a transformation in how the two communities interact. Without a transformation in this relationship, transformation of the nation's warfighting capabilities will be hampered.

The relationship that must evolve is one of constructive cooperation, which involves a great deal of listening on the part of each community. As the S&T process moves forward, there needs to be a continuous exchange of information and ideas. As new technologies emerge or fail to materialize, the operational implications must be thoroughly evaluated and priorities changed accordingly.

A double helix model will allow the S&T and operational communities to increase their understanding of each other's worlds through continuous interaction. As knowledge increases, both operationally and technically, decisions to transition new technologies to development and production can be intelligently based on realistic expectations and sound operational concepts. This double helix is not characterized by rigid *a priori* requirements or by visions of technology independent of operational relevance. Rather, it is characterized by a collaborative search for better technology and more innovative ways to use it.

There are cultural and bureaucratic obstacles to better operational and S&T cooperation. The long-term nature of S&T relative to the normal operational timeframe of interest is an obstacle. So too is the tendency to "approve" operational requirements at a high level, thus making it difficult or impossible for lower-level individuals to make changes based on new information. Most importantly, there is the attitude often encountered in both communities that it knows best, either about technology or about operations, and should therefore proceed independently to either set operational goals or to define S&T program objectives.

The task force believes the following recommendation can help to institutionalize this cooperative concept.

CONCLUSIONS AND RECOMMENDATIONS

This section summarizes the recommendations for science and technology investment priorities and for improving the relationship between the operational and S&T communities. They support the broad recommendations presented in the previous chapter.

INVESTMENT PRIORITIES

To attain the operational visions being pursued by the military Services, S&T efforts should be focused on high-payoff goals. The

military Services and the Joint Staff have operational visions of future warfare. In general, these visions include a networked, highly lethal, and agile force in which multiple capabilities are integrated using modern communications and computing. In addition to variations on or adaptations of some commercial technologies, these visions depend on the development of enabling technology that is uniquely military or for which commercial applications are limited.

While the commercial industrial base will provide some of the needed technology, much of it must come from DoD investments. Yet, DoD technology programs tend to be broad and comprehensive. As a result, the future capabilities required by combatant commanders and embedded in the various Service and joint concepts cannot be realized unless DoD focuses its technology development on those areas offering the greatest potential for transformational change in line with envisioned future war-fighting concepts.

Recommendation: The Department needs to focus its investment priorities on the nine priority areas below. These nine areas should be given priority for investment either because they represent the highest payoff areas or because they are associated with high-risk threats. The nine areas are

- ***Defending against biological warfare.***
- ***Finding and correctly identifying difficult targets.***
- ***Making timely, accurate decisions.***
- ***Enabling high-risk operations.***
- ***Missile defense.***
- ***Affordable precision munitions.***
- ***Enhanced human performance.***
- ***Rapid deployment.***
- ***Achieving global effects.***

In the view of the task force, S&T resources could be focused on these areas largely by restructuring existing efforts. Additional funding would of course be desirable, as was discussed in this and in the previous chapter.

Recommendation: Because of its potentially devastating effect and likelihood of employment, biological warfare defense deserves special emphasis.

The potential threat from biological agents, particularly from terrorist attack, but also as part of an access denial strategy, is devastating in its consequences. Much could be accomplished in this area, and the task force recommends a major effort to address all aspects of this problem, as previously outlined.

> ***Recommendation: When taken together, four other areas have the potential to provide fundamental transformation to support emerging concepts of operations and warfare. These are: finding difficult targets, making timely and accurate decisions, enabling high-risk operations, and developing affordable precision munitions.***

These four areas represent a suite of transformational technologies. The combined ability to find difficult targets, make rapid accurate decisions regarding engagement, and conduct those engagements in high-risk areas with efficient affordable munitions will transform warfare. Even though each Service has a somewhat different implementation in mind, the net effect and the suite of capabilities envisioned are similar. The Joint Staff properly captured this combination of capabilities in Joint Vision 2020. The technologies that would support this suite of capabilities have high synergy, both within the set and across Service applications. The task force recommends that the Department manage these technologies as a set of interrelated capabilities.

S&T AND OPERATIONAL RELATIONSHIP

Transformation of the interactions between the operational and technical communities is essential to transformation in general. The essence of this relationship must be active, constructive cooperation throughout the research and concept exploration processes. A double-helix model of spiral development would provide the basis for a successful process.

> ***Recommendation: The operational communities—the Services and the Joint Staff—should each appoint a single senior official as an interface to the S&T community.***

The authority of this official is critical for success. This official should be able to set operational priorities and minimum thresholds to drive S&T programs. The individual should understand and provide guidance on cost constraints for new capabilities that would inform S&T

leaders of the viability of proposed technologies for operational applications. Finally and very importantly for transformation, that individual should have the authority to decide what innovative operational concepts are worthy of Service investment in experimentation to explore the advantages and risks associated with new technology.

Focusing S&T investments on a set of high-priority areas and improving the relationship between the S&T and operational communities, will lead to successful transformation of the nation’s warfighting capabilities.

CHAPTER III

TECHNOLOGY

INTRODUCTION[18]

"Any sufficiently advanced technology is indistinguishable from magic."

– Arthur C. Clarke, Profiles of the Future: An Inquiry into the Limits of the Possible

This chapter focuses on technological "megatrends" that span areas as diverse as biotechnology, bionics, massive networked virtual environments, nanotechnology, and quantum computing and the opportunities they present for fundamental advancements for warfighting and national security. To the military leaders who have the responsibility of conducting current operations, implementing policies, and making priorities for investment, these technology concepts often have the tendency to elicit disbelief or, at the very least, intense skepticism. In some cases this is due to a lack of perceived relevance to military applications, and in other cases the time horizon looks to be so far away as to make it too difficult to justify DoD investment.

The urgency of today's needs and shortfalls dominates many investment discussions. However, it is important to make investments in today's megatrends, because such investments capitalize on areas of potentially explosive growth. Focused investment in emerging technologies can help DoD understand where and how new capabilities might arise for the United States and, since these technologies will be available globally, for our adversaries as well. These technologies also portend major shifts in the mindset and talents of both future scientists and future warriors, and thus are directly relevant to recruiting, training, and retaining talent.

An underlying assumption of this report is that the acceleration in the availability and globalization of advanced technology will continue into the foreseeable future. Thus every military organization—and indeed, every person—will be provided with unprecedented access to technology and thus unprecedented offensive and defensive capabilities. One can already catch a glimpse of what it means to live in such a world by observing current trends in information technology. Cyber-security incidents attract special attention because they reflect a basic fact about our technology-rich world: individuals possess technology powerful

[18] This chapter reflects the work of and was prepared by the Technology Panel of the 2001 DSB Summer Study task force. The panel membership, along with the government advisors and staff who contributed to this effort, is contained in Annex B.

enough to disrupt basic computing infrastructure on a global scale. There is no reason to expect this phenomenon to be limited to the information technology arena; indeed, the trend is clearly present in many areas of science and technology.

Another fundamental assumption of this report is that the technology landscape is no longer controlled or even predominantly influenced by the Department of Defense. The potential for rapid technological change demands great agility in exploiting new technologies, as well as a constant awareness of their potential impact on defense operations and policies. Achieving such agility is likely to require more than an understanding of science and technology; it almost certainly will require a change in the mindset of the organization and a willingness to "break the rules" of how the organization operates. If the nation fails to see an opportunity ahead of its adversaries or rejects an opportunity too early, it may be surprised.

Indeed, the task force believes that a primary factor limiting the Department's ability to become a technologically agile enterprise is that imposed by the artificial line between technology and warfighting. Modest progress has been made in experimentation and rapid prototyping methodologies, but the incentive structures are misaligned, resulting in mistrust, misplaced priorities, and missed opportunities in development. In a nutshell, DoD has chief executive officers (CEOs), but lack real chief technology officers (CTOs)—a role essentially relinquished to the contractor base. As a result, the CEOs do not have a history of interactions with trusted technologists and scientists who can advise them in decision making at all levels, and they do not have sufficient technical training themselves to do without. Similarly, too few technologists understand the demands and fundamental limitations of the warfighting environment. Thus, another overarching recommendation of this report is to improve the quality, frequency, and content of the interactions of these two groups throughout the Department of Defense.

This chapter begins with an overview of today's technology landscape, providing a preview of the "megatrends" that form the basis for the main recommendations. It then discusses four technology initiatives that the task force believes have the right characteristics to form the basis for sound investment. Broadly speaking, these projects lie in the areas of biotechnology, information technology, sensors, and robotics. The chapter then turns to a discussion of promising areas of more basic research, specifically nanotechnology and quantum computing. Discussions of several other important areas can be found in the annexes to this report;

topics include power systems, unmanned systems, and the novel concept of a "remoter force."[19]

A well-balanced science and technology approach must both address the needs of current operations and look well into the future. This chapter focuses on the latter—on technological opportunities, rather than currently articulated needs. This perspective means that the concepts and recommendations discussed herein are not all encompassing, nor are they notional examples. Instead, this chapter focuses on a small number of research areas that, if brought to fruition, would result in dramatic improvements in warfighting capability as well as enhance the vitality of DoD's science and technology enterprise.

THE TECHNOLOGY LANDSCAPE TODAY

The nation's future talent pool has grown up using computers fearlessly; electronic gadgetry is part of their everyday lives. Social interaction takes on many forms, many of which do not require physical presence—such as instant messaging, participation in massive virtual environments, and collaborative information exchange. But the fact that this new talent pool has substantially more access to information technology is only part of today's technology landscape. Other areas of science are also producing capabilities that might have been unimaginable only a few years ago. Notably, many of these are not capabilities on which the Department of Defense has set its sights for the future. But there is no argument about their feasibility—they are here now.

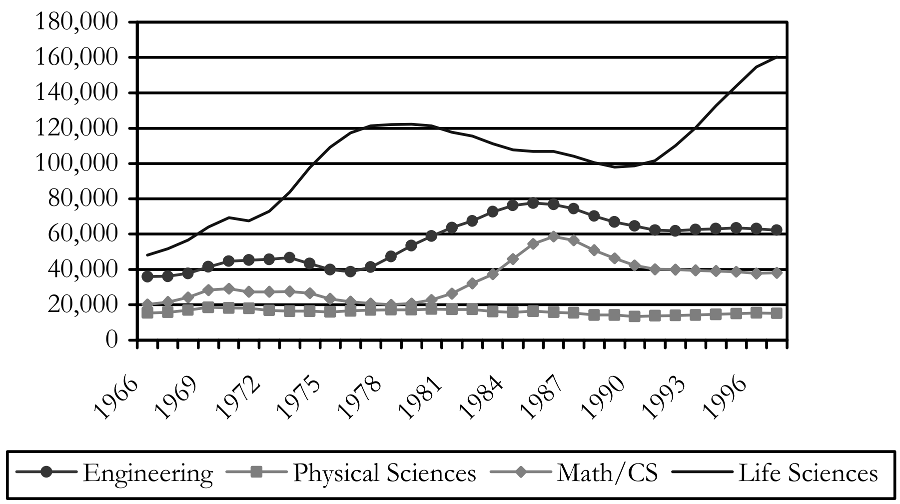
BIOTECHNOLOGY

On February 15, 2001, a 95%-complete draft of the human genome was published in the journal *Nature*, with a 99.99%-complete sequence projected for 2003, several years ahead of the originally envisioned schedule. The grand vision and rapid pace of progress on the Human Genome Project has helped spark an enormous shift of the world's science and engineering talent pool towards the life sciences. (See Figure 3-1.) The combination of inspirational vision, an enormous talent pool, and aggressive applications of advanced technology has led many scientists

[19] Discussions on power systems, unmanned systems, and the remoter force can be found in Appendix E, F, and G, respectively.

and analysts to predict that the world is now entering into the "era of the life sciences." Indeed, the rate of progress in this field appears to be accelerating rapidly, with applications to human life emerging on a daily basis.

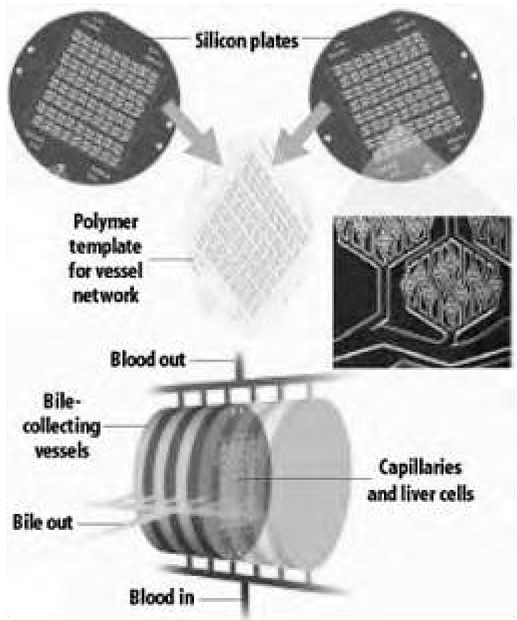
Figure 3-1. S&E Bachelor's Degrees Awarded



Source: From the Higher Education General Information Survey and the Integrated Postsecondary Education Data System.

Importantly, the ability to engineer devices on length scales approaching the physical dimensions of biological construction has created a host of new opportunities, just beginning to be realized. For example, biomedical engineers have demonstrated the feasibility of growing entire blood vessels on demand. Experiments are being conducted to etch capillary-like grooves into silicon wafers, seed the grooves with endothelial cells, and grow capillaries as small as 10-20 microns in diameter, as illustrated in Figure 3-2. Some day, it might be possible to grow complex organs such as artificial livers.

Figure 3-2. Growing artificial livers.

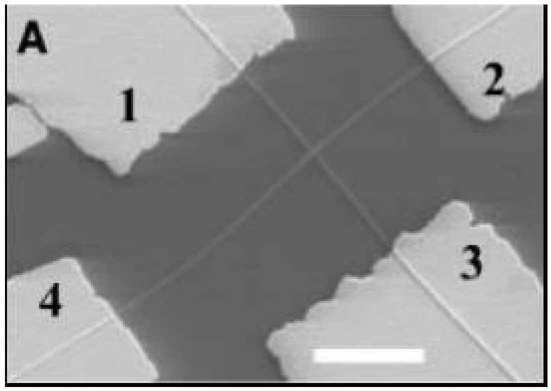


Source: Technology Review, April 2001.

NANOTECHNOLOGY

Equally startling is the recent progress in nanotechnology, particularly in molecular-scale electronics. Today, the design and manufacture of electronic components at the atomic scale is possible in the laboratory, with companies such as Hewlett-Packard demonstrating molecular-scale memories (shown in Figure 3-3) 10 times smaller than conventional CMOS memories. Other demonstrations include an n-p-n nanowire transistor that shows a high 16x gain and a resonant tunneling diode with lower temperature on-off ratio greater than 1K. In university laboratories, multi-transistor logic circuits at molecular scale are now being demonstrated.

Figure 3-3. An operating nanotube molecular memory.



Indeed, the concerns that researchers might never manage to link such devices together into complex circuits, while still serious, diminished significantly last year, leading *Science* magazine, for example, to name the first complex molecular-scale circuits as the "Breakthrough of 2001."[20] The full impact of such emerging technologies are possibly many years away, but what these and other demonstrations show is the feasibility of nanoscale computing devices that could have on the order of 10^{10} gates but consume less than 2W of power. If realized, such a capability would represent a two order-of-magnitude improvement in density and an order-of-magnitude improvement in power consumption. Such devices would provide unprecedented computing power in small battery-operated devices and "provide computing power to launch scientific breakthroughs for decades."[21]

Besides molecular-scale electronics, nanotechnology also has the potential to revolutionize materials engineering, leading someday to ultra-high-strength lightweight materials, massive arrays of microsensors, and ultra-sensitive chemical/biological warfare agent detectors.

UBIQUITOUS COMMUNICATION TECHNOLOGY

Surrounding the technological innovation in almost all science and engineering fields is an explosion in ubiquitous communications technology. Today, digital data traffic exceeds voice traffic on global telecommunications networks. Much of this progress is fueled by

[20] "Molecules Get Wired", *Science*, 294, pp 2442-2443.
[21] Ibid.

commercial demand, which last year led private companies to lay more than 60 million kilometers of fiber-optic cable and researchers to develop new network switching technology that increases bandwidth from 135 megabits per second in 1983 to over 1.6 terabits per second in 2001. Augmenting this high-bandwidth communications backbone is a proliferation of access to wireless communications technologies, with over 490 million new mobile handsets sold last year, involving over 450 million cellular subscribers.

Today, in order to be competitive, most large organizations, including the Department of Defense, find it necessary to exploit these dramatic increases in communications capabilities. Interestingly, to do so, many companies look to young people. Not only do young people represent the emerging talent pool, but they are also the focal point for several key future markets. For example, Nokia, a market leader in mobile wireless handsets, uses children of ages 12 to 18 to study the usefulness and appeal of communications features such as new modes for wireless instant messaging.

On the cutting edge of these communications-enabled markets is arguably the most robust information-technology sector, namely the online entertainment industry. Last year, video gaming and online entertainment companies grossed over $9 billion, an amount on par with (and actually exceeding) the U.S. market for motion pictures and videos. Video games and consoles continue to be one of the fastest-growing information technology market sectors, and one of the few sectors whose demand for increasing amounts of computing power continues to increase rapidly. As such, the video game market—a market made up primarily of youths who at age 18 have more than 1,500 hours of video gaming experience—drives the development of increasingly powerful graphics processors, and overall is one of the most important drivers for the development of more powerful computer processors.

In the realm of video games, the level of graphical and physical fidelity has been improving steadily, to the point where professional pilots of airplanes and racecars use games such as Microsoft Flight Simulator and Psygnosis' Formula 1 for both entertainment and training. However, a recent development of potentially greater impact involves the rapid emergence of massive multiplayer (MMP) environments such as Ultima II Online, EverQuest, Lineage, World War II Online, Anarchy Online, and others. These games allow a person to use the Internet to enter into a massive virtual world, assume the identity of an "avatar," and interact with tens of thousands of other people through their avatars. Instead of focusing purely on hand-eye coordination and reaction times, these games

emphasize the collaborative development of self-organizing societies, rapid development of tactics, and experience-based learning.

S&T INVESTMENT

In contrast to the science and technology landscape of 40 years ago, the Department of Defense is no longer the major "customer" for new technologies in the commercial sector. Advanced technologies must be marketable to a large and willing customer base in order to yield favorable returns. The Department of Defense is neither, and the profits from R&D contracts are not attractive enough to many commercial companies in the absence of follow-on acquisitions.

Corporate investments in science and technology R&D dominate the landscape. Microsoft Corporation spent over $2 billion on the development of the Xbox video game console. Corporate investments in nanotechnology are now approaching $1 billion. A single pharmaceutical company, GlaxoSmithKline, reported a research and development budget of nearly $4 billion in 2000, and it is expected to climb to approximately $5 billion in 2002. Commercial research and development in information technology is projected to exceed $50 billion in 2002. The top 20 industrial R&D spenders[22] had a combined budget of nearly $100 billion in 2000; this is compared to approximately $40 billion for the entire DoD research and development investment for the same year. While it is sometimes argued that industrial R&D budgets are focused primarily on near-term product development, this point is only partly valid. Both private companies and the DoD are required to do a good deal of development in their R&D programs. And, like DoD, about half of the top 20 industrial R&D spenders have a significant commitment to basic research. For these companies, R&D budgets as a percentage of sales range between 10 and 20 percent.

Significantly, foreign countries are increasingly at the vanguard of the deployment of the latest technologies, most of which are developed in the United States. For example, many developing countries "leapfrog" the need for conventional wired networks by exploiting wireless technologies, with the result that the wireless infrastructure outside of the United States is often superior and more pervasive. In basic science, in what was once a rare occurrence, Chinese scientists are now routinely publishing papers in the journal *Science*. The most successful massive multiplayer game today,

[22] Ford, General Motors, DaimlerChrysler, Matsushita, Lucent, Nortel, Siemens, Motorola, Toyota, Sony, Hitachi, Ericsson, Pfizer, Cisco, IBM, Fujitsu, Microsoft, Nippon, Intel, Honda. (GlaxoSmithKline is number 21 with an R&D budget of $3.7B in 2000.) Ref: Schonfeld & Associates, Inc. "R&D Ratios & Budgets".

called *Lineage*, is not even available in the United States, but only in Korea and Taiwan. In fact, several market research firms estimate that about 10 percent of the Korean population subscribes to at least one MMP game, and over 4 percent to *Lineage*, to which about 110,000 Koreans log in each night. Predictably, Korean teams have been dominant in the annual worldwide video-gaming Olympiads.

REVITALIZING THE S&T ENTERPRISE

It is in this fast-paced environment that the Department of Defense must compete—for talent, to set the pace, and to exploit explosive technological changes and trends. As such, the S&T challenge for the DoD is not purely a technical one, but also involves the management of technological innovation. How can the Department do what is right for near-term health, while simultaneously focusing adequate resources and attention on potential disruptive technologies that ultimately could become decisive factors in national defense? To find answers to such a question requires a degree of nimbleness that may be lacking in some aspects of science and technology strategy of today's Department of Defense.

The Department of Defense understands the importance of bringing committed talent together and creating, through special management and visionary leadership, a culture of innovation and a "magnet" for attracting and retaining top talent. Some of the most astonishing science and technology discoveries in history have been at the hands of "great groups" working for the Department of Defense. The Manhattan Project and various "skunks works" are but two examples. These achievements were the result of individuals brought together with purpose, often against conventional wisdom and the odds, to work on what to many might have seemed impossible or foolish. But these endeavors were the works of visionaries with a keen eye for military relevance. In each case, they were handled outside the established order, "working in the white spaces" outside the organizational chart and protectively buffered from the mainstream.

The S&T projects discussed in the remainder of this chapter were identified in part because of their visionary nature. They are visionary in their importance to the nation and hopefully in their ability to recruit and retain top talent in much the same way that focused visions such as the Human Genome Project have attracted thousands of young scientists into the life sciences. When it is approached properly, the main limitation in hiring top people should be less an issue of pay or benefits than one of creating the belief that they will be well used. Within today's DoD, DARPA has a charter that is consistent with this goal, and thus it is

already well-suited to managing some of the recommended projects. For other projects, new organizational structures will likely be needed. In all cases, the projects should consist of multiple people, technologists, and operators who are given complete end-to-end responsibility with the ability to engage in direct, intimate interaction, and experimentation.

BIOLOGICAL WARFARE DEFENSE: PATHOGEN TO "HIT"

The threat of biological weapons arises in part from a decades-old megatrend in the life sciences. New advances in molecular biology, genetics, and related areas such as combinatorial chemistry have yielded new discoveries in the treatment of disease, in the development of new drugs, in agriculture, and in other fields. They have also yielded new weapons in the hands of adversaries. Perhaps the single most significant modern challenge to U.S. sovereignty is that created by the possibility of a massive biological attack. It is a threat to the United States' military, it allies, and its homeland. Biological weapons can be delivered at the hands of a few, and they present a small signature for which the United States has ill-developed intelligence-gathering capability, against which conventional concepts of deterrence are not necessarily effective, and for which the nation has a limited response capability to contain the consequences. The task force argues, as others have before, that the only strategy is to broadly address all dimensions of defense from new deterrence measures to new therapeutics. The Department of Defense needs an integrated biological warfare defense program.

The Biological Defense study conducted by the Defense Science Board and the Threat Reduction Advisory Committee made the following conclusion: "The present U.S. defensive effort … will not effectively counter the current threat [of biological warfare]" and is "hampered by an absence of a vision of what is required … lacks leadership and coherent organizations." As discussed in Chapter 1, three DSB studies have made recommendations for a DoD-wide strategy for bio-warfare defense. The task force supports the recommendations of these studies to rapidly increase defenses, including the conduct of near- and far-term S&T efforts as well as the effective exploitation of "low-hanging fruit" such as the stockpiling of vaccines and therapeutics. The recommendations need to be implemented. In addition, the task force recommends the Department embark on a new technology project pathogen-to-hit, also referred to as "Bug-to-Drug in 24 hours."

BACKGROUND AND HISTORICAL PERSPECTIVE

Interestingly, some of the earliest developments in biology were rapidly embraced and developed in response to defense needs. "In 1929 Alexander Fleming discovered that the growth of bacteria was inhibited in the presence of penicillium molds."[23] A strong military need drove the rapid practical development of large-scale production of this antibiotic for use in the war effort. "During the war, the American pharmaceutical industry was given the task of producing penicillin on a large scale. With the development of submerged cultures (as opposed to the surface cultures used initially), large quantities of penicillin could be produced to meet the demand created largely by the great numbers of wounded."[24] This historical footnote aside, the Department has largely failed to exploit the rapid developments in the life sciences, and as a result is behind in its ability to combat the threat posed by these advances and to attract the talent necessary to develop the needed capability.

In contrast, private investments in biotechnology and the life sciences have "grown, matured and evolved immensely since the first wave of biotechnology entrepreneurs in the late 1970s. In 1980, the year in which Genetics Institute and Amgen were founded, there was a total of approximately $500 million invested in healthcare venture capital compared to $5 billion in the year 2000."[25]

Coincident with this growth in the life sciences, the end of the Cold War created new opportunities for smaller and emerging powers to expand their influence and doctrine. The Gulf War taught the world that fighting the United States on its terms in formal military combat is futile. As a result, these emerging powers (that is, both state and non-state/religious terrorist organizations) have been considering, and to some extent developing, biological weapons as part of an arsenal for use against the United States and its allies.

Naturally occurring outbreaks of disease have wreaked havoc for generations. Small pox caused some 400 million deaths in the first half of the 20th century, and the 1918 flu pandemic caused 20 to 40 million deaths, having swept the globe in just six months. Some U.S. cities experienced more than 10,000 deaths per week, and overall 500,000 Americans died. People were quarantined; ignorance and fear reigned. The

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23 *In Quest of Tomorrow's Medicines*. Jürgen Drews. Springer, 1999.

24 Ibid.

25 "Trends in Biotech Business Models: The More Things Change, the More They Stay the Same." Bryan Roberts, Venrock Associates. The Biotechnology Club Network.

effect of this pandemic was so profound that the average life expectancy in the United States was depressed by more than 10 years. And in June of last year in Ohio an outbreak of a non-contagious disease from a known pathogen created a local panic and made national news. Three patients were initially identified; the Center for Disease Control and state health officials were 99.9 percent sure of the identity of the disease but could not confirm it quickly. This situation resulted in the emergency transport of antibiotics from three states and the administering of antibiotics to 37,000 people. Indeed, global infectious disease is biological warfare in the hands of Mother Nature.

Whether the objectives of terrorism are regional or worldwide, as of September 11, 2001 terrorism has escalated to using weapons of mass destruction (e. g., U.S airlines) within the shores of the United States. Important implications of this horrendous attack include terrorists

- Have invaded CONUS.
- Are willing to use weapons of mass destruction to cause great loss of life.
- Are willing to sacrifice the lives of their own to accomplish such attacks.
- Have the patience, experience, and resources to plan and execute such attacks.

These revelations suggest additional, as yet unproven, thoughts that such attacks may:

- Only be the opening move of a larger war-by-terrorism within the United States.
- Extend beyond the United States to the territory of its allies.
- Inspire other terrorist organizations into action.
- Expand to include use of nuclear, biological, and chemical weapons of mass destruction.

Terrorists have demonstrated the resources and capabilities to destroy the World Trade Center and a part of the Pentagon; with this same level of resources and capabilities, these (and other) organizations could implement selected BW attacks. Also, the emergence of these hidden cells means that the conventional thoughts about deterrence do not apply. The potential for the use of BW in a large-scale terrorist activity against the United States has never been greater.

BW has many features attractive for terrorists with the profile described in the list above. Significantly, BW capability costs less to

acquire in time, facilities, and expertise than its nuclear analog. Further, unlike nuclear technology, virtually all of the technical components, including most pathogenic organisms, needed to develop a dangerous BW infrastructure remain readily available through completely unclassified literature and microbial collections. While some reports have questioned the practical feasibility of biological weapons—citing the requirement for large quantities of complex, specially formulated pathogens delivered by cumbersome mechanisms as barriers to their use—these conclusions apply primarily to tactical military situations. In the context of terrorism, these basic limitations are not necessarily applicable.

Well-resourced BW terrorists, even in the absence of advanced molecular biological expertise, have a menu of at least one hundred naturally occurring microorganisms from which to select a wide array of effects. These effects range from diseases with acute and rapidly fatal results to those with slow, highly contagious and, hence, farther-reaching effects. Furthermore, the targeting possibilities for generating terror within a free society such as the United States' are endless and only limited by the terrorists' creativity and desired objectives. One does not need to fly a crop duster over the Washington, D.C. area to cause widespread disease and panic. Clever application of small aerosol devices with appropriate microbes in a stadium or an airport can provide desired effects, long after the perpetrator is gone. The terrorist, unlike his military counterpart, does not have to overcome his enemy to obtain his objective; rather, the terrorist can accomplish his mission by inflicting almost any degree of documented suffering to an unsuspecting populous, as long as a wide-based perception is created that more is possible. This feature creates an "I-can-touch-you-anywhere-anyhow-anytime" terror.

Nothing in this summary regarding BW's potential is new. However, the tragic events of September 11, 2001, have demonstrated to the world the resolve of at least one terrorist organization to inflict death and injury on a massive scale against innocent people. With the moral barrier to such destruction compromised, the task force believes that the willingness to use BW, particularly as a weapon of terror, has increased.

Towards a Comprehensive Biological Warfare Defense

The 2001 DSB/TRAC Biological Defense Study, co-chaired by George Whitesides and Josh Lederberg, outlined a vision for comprehensive biological warfare defense. Importantly, the study concluded that biological warfare defense was not "too hard" to counter

and that both long-term and short-term actions would do much to mitigate the threat. Several areas of emphasis were articulated in the DSB/TRAC report, and that study's findings are firmly endorsed here. The nine components of this strategy appear below:

1. Effective intelligence and awareness.
2. Capability for warning and characterizations of attacks.
3. Capability for vaccination against biological agents.
4. Widely available means of passive protection, including masks and citadels.
5. Rapid, effective incident and crisis response.
6. Access to therapeutics to minimize casualties during an event.
7. Capability to decontaminate and restore function.
8. Forensic capability to guide attribution, retribution and deterrence.
9. International laws and treaties and methods of enforcing them that prevent the development and use of biological weapons.

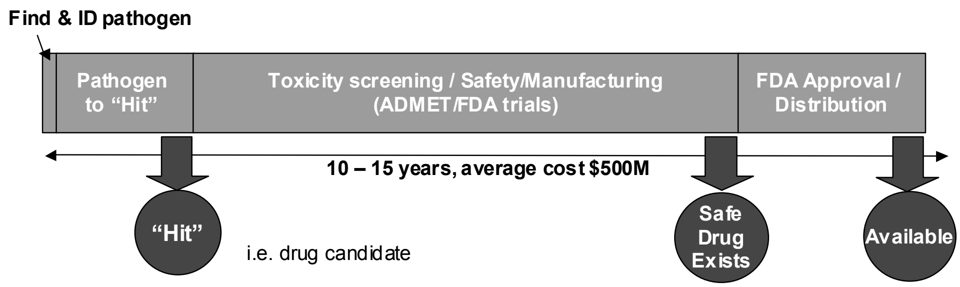
An effort to unify these considerably broad efforts in a comprehensive manner has not yet occurred within DoD. An integrated defense will require, in addition to incremental and near-term efforts to harvest the "low-hanging fruit," the acceptance of bold challenges. The 2000 DSB Task Force recommended the creation of an advanced diagnostics capability, the "Zebra Chip;" the fundamental pathogen databases; and the integrated epidemiological reporting system that accompanies it. The Zebra Chip Project is itself an important technology initiative, as is the project proposed below. It is vital, however, to recognize that the implementation of this initiative is best considered as part of a broader and unified effort, which would address every component of the proposed system needed to deal with biological warfare.

THE CHALLENGE: BUG-TO-DRUG IN 24 HOURS

The task force asserts that biological weapons are weapons of terror because the United States lacks adequate therapeutic responses. Further, the ability to generate a therapeutic response and control the consequences of an attack would be a deterrent. Figure 3-4 gives a schematic for the drug development process, showing that the development of a new drug

takes approximately 10-15 years and costs on average $500 million. DoD should undertake a technology initiative to compress key elements of this process.

Figure 3-4. The drug development process



By 2005, the DoD should create the capability to compress the pathogen-to-hit process from years to months. It should demonstrate this ability by using intelligence reports on new BW agents to create "hits"[26] within a month of identification and to screen for therapeutics against these new pathogens from existing antibiotics. Additionally, this accelerated process should be used to create hits for the top 50 known BW targets. As part of this effort, new approaches to compressing toxicity and safety screening and manufacturing should be investigated.

By 2010, the DoD should create the capability to compress the pathogen-to-hit process to weeks and the toxicity and safety screening processes by a factor of ten. The manufacturing process should be compressed by 50 percent and yield and shelf-life methods should be improved 10-fold. Construction of large and dedicated manufacturing facilities should be initiated based on improved methodologies.

By 2020, the DoD should create the capability to compress the overall process from identification of a new pathogen to viable drug to 24 hours, under emergency conditions. Manufacturing facilities should initiate production, and the process for emergency manufacture should be brought to within days or weeks.

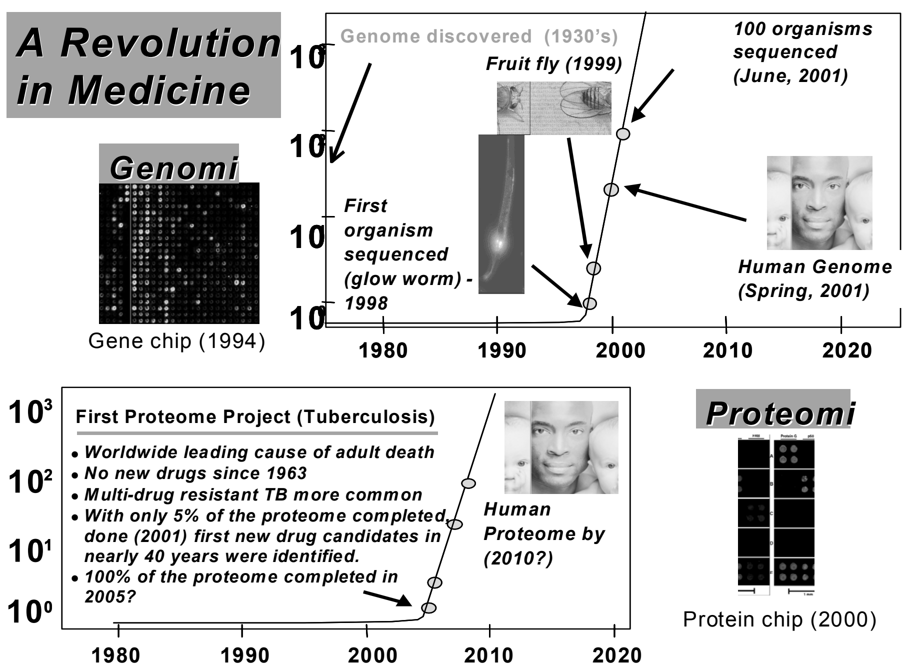
[26] A "hit" in the vernacular of the drug development process refers to an initial match between the disease or pathogen target and the drug that elicits a favorable response at the target site. As an example, this might be a particular chemical that interferes with a critical molecular signaling pathway necessary to the survival of a virus. Additional steps are required to turn a hit into a safe drug.

The estimated cost of such a program is $100 million per year, and the goals are 20-year goals. This project will necessarily require significant collaborative efforts between industry, academic, and government personnel. The collateral benefits and implications for world health are staggering.

The Promise of an Improved Process

Such a program cannot be postulated, without describing some of the current advances that inspire such vision. Figure 3-5 illustrates some of the exponential trends fueling the revolution in medicine and the life sciences.

Figure 3-5. Genomics and proteomics in the life sciences.



Within drug development itself, the process of generating 'hits' has decreased from between three and five years to between nine months and three years in the last decade. This advance has been fueled primarily by modern genomics and proteomics, which provide an abundance of targets and data sets that decrease the time for target validation. Two examples loom large:

- A mere 5 percent of the proteome for Tuberculosis resulted in creation of the first new drugs to treat the disease in more than 40 years.
- A detailed understanding of protein structures resulted in the development of the first drugs that inhibited AIDS.

Furthermore, the development of drugs that more tightly target key molecular biological events shows the promise of dramatically reducing toxicity and safety concerns. As an example, the development of Gleevec[27] for a rare form of leukemia (chronic myeloid leukemia) was designed to attack key molecular pathways in the cancer cells themselves. The Food and Drug Administration (FDA) approved Gleevec after only a 2.5-month review of clinical data. A relatively small set of patient data was submitted, but the data was so compelling and the disease so life-threatening that the drug was rapidly approved for use.

Many commercial entities seek to further streamline the drug discovery process through the use of high-throughput techniques for genomics, proteomics, and cell-based assays; the development of protein-folding predictions from first principles; and the computational optimization of drug candidates. DoD should drive the processes that industry, academia, and the National Institutes of Health (NIH) do not, to include the building of reference databases for potential BW threat agents, the design of FDA-specific clinical protocols for new BW therapies, and the development of accelerated and high-yield manufacturing processes. DoD should also seek to leverage its computation expertise to accelerate first-principle approaches and in agile manufacturing, to build both a research and a development bridge to the pharmaceutical industry, NIH, Center for Disease Control, and FDA, and to serve as the "systems integrator" for the accelerated approach described herein.

Recommendation: The DoD should increase S&T spending in support of a comprehensive biological warfare defense capability from $250M per year to $1B per year.

The DoD should undertake a project to dramatically reduce the time from "Bug-to-Drug" with the objectives outlined above. The cost of this program is approximately $200M per year, and it should be considered a 20-year program.

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27 Gleevec is a product of Novartis.

NO PLACE TO HIDE: MICROSENSOR NETWORKS

Recent experience in Bosnia and Kosovo has demonstrated the capabilities of adaptive enemies and has indicated the extreme difficulty of remotely targeting military vehicles and forces hidden under foliage, in buildings, and in underground facilities. Such targets traditionally have been pursued by ground troops who often suffer losses in the process.

Surveillance and reconnaissance systems, both present and planned, are predominately based on active or passive electromagnetic remote sensing from airborne or spaceborne platforms. These systems exhibit significant problems providing critical surveillance and targeting data, especially in real time. First, remote sensors perform inadequately in certain environments, such as in urban canyons or under foliage. Second, enemies can engage in camouflage, concealment, and deception by timing activities to coincide with gaps in coverage or by masking or duplicating the remotely sensed signatures. Third, many types of information cannot be satisfactorily or cost-effectively obtained by remote sensing.

The Defense Science Board has discussed the technological developments required to mitigate some of these shortcomings in previous studies. One promising solution is to complement standoff sensors by placing shorter-range sensors in the area of concern and to read out those sensors remotely, permitting continuous sensing of a wide range of signatures. Many interesting observables are present at close ranges, but are difficult or impossible to sense remotely. They include

- DC to mm-wave electromagnetic emissions.
- Magnetic fields and magnetic anomaly detection.
- Acoustic signatures, including Doppler shifts.
- Chemical emissions: single substance detection to full chemical analysis.
- Biological agents: detection, quantification, or agent identification.
- Nuclear radiation.
- Pressure and vibration sensing.
- Air-flow sensing.
- Short-wave ultraviolet emission.
- Infrared emissions.

- Imaging, object recognition, or image change detection.

Though close-in point sensors exist today, their utility has been severely limited for several reasons. First and foremost, the power consumption requirements of the sensors, combined with limitations in battery technology, have resulted either in large, battery-dominated sensors (such as those used in Vietnam), or in smaller sensors with very limited functionality, transmission range, and mission lifetime. Limited-range, "dumb" sensors do not provide wide-area coverage. The size, cost, and performance of current sensors, combined with the difficulties in emplacing them, have limited their use to small numbers in proximity of high-value targets. In addition, the technology has not existed to create very low-cost sensors or even those capable of sensing several observables, such as chemical or biological agents; emerging technologies promise to dramatically alter that situation. Finally, point sensors have been viewed as either stand-alone devices or for use in locally controlled clusters. An architecture that integrates these into a wide-area, information-on-demand surveillance system has not been developed.

TECHNOLOGICAL OPPORTUNITIES

Advances in energy sources, microsystems technology, and biotechnology promise low-cost, miniaturized sensors that could be cost-effectively distributed over a theater of interest, providing real-time, continuous, all weather, day-night surveillance. An enemy could not practically evade such coverage. Key attributes of the proposed capability are as follows:

- ***Ability to measure a wide range of signatures***, making concealment and deception a very difficult problem for an enemy and greatly reducing his mobility and agility.
- ***Continuous*** real-time monitoring, with information provided on demand through a wide-area network controlled from overhead or terrestrially. Utilizing an aircraft, or a space-based system employing a large-aperture sparse-antenna array, the sensors can be geolocated and "polled" to deliver their unique identification and stored data. Alternatively, ground-based networking options allow a secure, low-power communications network with a robust connectivity and low probability of detection. Forces operating in the area could use this network. Because data delivery would typically be in short bursts and the timing of transmissions

would be remotely controlled by the user, major power reductions and improvements in covertness could be expected compared with present systems. Sensors could be kept dormant until needed or commanded to report back only if high-value events were detected.

- ***Small-size and low-cost*** sensors (on the order of one cubic inch and costing less than $10 each). Such sensors could be dispensed in overwhelmingly large numbers (such as 100,000 sensors over a theater of operations), which would not only enable wide-area coverage from what is essentially a point sensor, but also make location and neutralization very difficult for the enemy. Even less-expensive decoys could further complicate detection and cleanup by an enemy.
- ***Covertness***, which would be achieved through small size, camouflage, mobility, and low-probability-of-detection communication enabled by on-board intelligence. However, depending on the application, the very use of large numbers of sensors, coupled with extensive intermixing of "penny" decoys, might obviate the need for covertness by simply overwhelming the enemy with too many sensors to pick up or destroy. A sensor survival rate of as little as 20-30 percent could still provide the required functionality.
- ***Survivable systems***, capable of long-duration operations. Depending on the sensor type and intended application, and particularly on advances made in power-supply technology, conceivable operational periods of the network (not necessarily of an individual sensor) range from months to years.
- ***Effective deployment and emplacement***. Non-traditional deploy-ment means may be used—such as "crop dusting" or "air burst," inadvertent transport into inaccessible areas by the enemy (sensors clinging to vehicles or clothing), or the sensor's own robotic or biologically aided mobility. Other means could be used as well, such as artillery delivery and hand emplacement (sowing), either overtly by troop units or covertly by operatives behind the lines.

Such a system could have covered Kosovo with sensors spaced approximately every 30 meters, at a total cost of only several tens of millions of dollars for the sensors. The data from these sensors, integrated

into a C4ISR system with other data acquired from more traditional standoff sensors, would have provided a comprehensive view of the battlefield, enemy capabilities, and enemy intentions. Of particular interest is that such a sensor system would have the capability of gathering information on weapons of mass destruction, of characterizing concealed and hardened facilities, and of providing information on targets obscured by foliage.

Achieving sensor system goals will require significant developments in the overarching technology areas of energy, microsystems, and biotechnology.

Table 3-3 captures the principal attributes required for a sensor network and shows that an improvement of 10-to-100-fold is needed in several of the technologies to make ubiquitous, inescapable, intrusive sensing possible. Some key areas where research is needed are energy sources, microsystems, and biotechnology.

Table 3-3. Technological Developments Needed for Close-in Sensors

	Today	Current Technology Trend	Needed Advances	Key Technology Area
Networked	2-10	100s	10-10,000x increase in number	Information tech. Microsystems
Lifespan	Hrs – days	Low-power electronics + energy extraction => 2 weeks	10-100x increase	Microsystems materials & materials
Ensemble	4-5 physical sensors	Polymer films for chem sensing, bio assays-on-chip	10-20 bypes of sensors: physical, chem, bio	Biotechnology, materials, & energy and microsystems
Undetectable	Coke-can-shoe box size: fixed	>1mm^3 seismic sensor, 3D packaging	10x decrease in size intrusive e.g. biosentinels	Microsystems, materials & energy biotechnology
Affordable	$1,000/sensor	~$5 MEMS accelerometers	100x decrease	Microsystems
Deployment	Hand-emplaced	Lighter, smaller => min shock resistant, aerodynamic structures	UXV emplace, high alt. Air dropped, 100-1000x increase (in emplace rate)	Materials & energy microsystems information technology

Energy sources. A mix of sensors is envisioned, ranging from low-data-rate seismic sensors to high-data-rate video sensors. While some of these sensors would achieve the desired lifetime with today's batteries, others will need about 10-100 times more energy than can be provided by present-day batteries. Two approaches have been identified that could lead

to such an improvement: very high-energy-density materials and energy harvesting from sources (physical and chemical) in the local environment.

Microsystems. Achieving the critical size, weight, and cost targets that are necessary for close-in sensors will only be possible if nanoscale miniaturization and mass-production techniques are developed. Developments in micro-electro-mechanical systems (MEMS) for sensors, especially for the microfluidic manipulations needed for chemical and biological identification, will be critical. A special focus on increasing the level of integration while controlling process cost is critical to success. MEMS will also play a critical role in interfacing with biological systems, providing mobility, and reducing the cost and complexity of the communications subsystems. Lower power and more highly integrated electronics, as well as efficient algorithms, are essential to enable the sensors to process locally signature data, thereby minimizing the quantity and frequency of data transmission. This advance would reduce both power consumption (communication is very costly) and probability of detection during communication. For certain sensors, a reduction in power-per-operation of more than 10,000-fold may be needed from present day levels. Ultimately, nanotechnology, as discussed in a later section, should provide substantial further improvements in capabilities.

Biotechnology. Development of low-cost sensors capable of detecting and fully characterizing bioagents will become possible with sustained and focused work in the biotechnology area, as discussed previously. Biotechnology may also provide other quantum-leap technologies that could result in dramatic new capabilities in miniature form factors. For example, the successful integration of electronic microsystems with living organisms, such as insects, could provide new delivery systems for the sensors, or impart mobility. Biological systems or processes could provide the basis for generating energy at the sensors by using materials present in the local environment, just as living organisms do. Chemical sensors (odor detectors) provide yet another example of sensing capabilities that might be possible through biomimetics.

MASSIVE ARRAYS OF GROUND SENSORS

The task force agrees with previous DSB study conclusions in proposing that the DoD undertake the creation of a new class of surveillance capability, involving the use of as many as 100,000 to 1,000,000 microsensors distributed over a theater of operations, but concentrated in critical target areas. These micro-sensors would be able to

provide continuous surveillance of concealed and moving targets with an array of different detectors, such as biological, chemical, optical imaging, acoustic, seismic, and electromagnetic sensors. Advanced energy systems coupled with covert communications would transmit data to relays and overhead receiving systems for processing into detection, identification, and target data.

In future systems, some of the microsensors might have ground or air mobility to allow advantageous placement and observation. It is anticipated that some degree of robot intelligence could be incorporated to enable the micro-sensors to investigate concealed targets on their own.

This class of surveillance and targeting system, integrated with greatly improved versions of the more conventional remote air- and space-based sensors via a C4ISR capability, should allow future U.S. military forces to find, identify, and target aggressor military equipment and forces that are concealed under foliage, in buildings, and perhaps in underground facilities. In addition, such a sensor capability should allow identification and targeting of moving targets, even under foliage.

Many technologies needed for these miniaturized sensors are already under development with support by DoD or the commercial sector. For example, a current five-year program in the Army is developing an increasingly capable network of small sensors that can detect many, but not all, of the signatures described above. These sensors are small, easily deployable, are able to function unattended for three to four months, and are locally netted together on the battlefield.

To achieve more sophisticated sensor capabilities (such as video-based and bio-sensing capabilities), longer lifetimes, and truly strategic capabilities such as country-wide coverage by sensors with real-time, remote polling, and on-board data processing, these developments will need to be continued and expanded. This endeavor will lead to evolutionary improvements in conventional point sensors, as well as lay a technological base for rapidly applying more radical concepts from the biotechnology, nanotechnology, and quantum computing areas.

Indeed, to achieve the dramatic technological capability needed to make feasible the ultra-low-cost, highly capable, and proliferative sensors described above, focused investment is necessary in "stretch" or "radical" technologies. Focused investments on approaches that could lead to leaps in capabilities in energy systems, microsystems, and biotechnology are essential. It is worth noting that these technological developments are expected to have a broad impact across a wide range of DoD systems and to enable significant civilian dual-use payoffs.

While civilian technology development is proceeding in some of these areas, most of it is focused on the near term. These technologies should be combined to demonstrate initial military capabilities.

Recommendation: A program should be established, focusing on advancing technology in a variety of ultra-small sensing devices, micro-high-energy-density technology, microrobotics and air vehicles, covert communications technology, ultra-small data processors and memories, and the integration of these into very small, low-cost systems. That program should also be responsible for integrating these into a pervasive sensing system. An appropriate level of funding is $150 million per year, sustained over at least a five-year period.

10^N WARGAMING: PEER-TO-PEER WARGAMING

In 1999, the DSB conducted a study on training superiority and training surprise. It investigated the current state of military training and readiness, leading to the following findings:

- Some forms of training can deliver order-of-magnitude improvements in warfare proficiency in as little as two weeks.
- Warfare in 2010 and 2020 will require more training, not less.
- The acquisition and testing process pays little attention to how a weapon system will be provided with trained operators and maintainers.
- Inadequate and poorly timed training will negate the technical superiority of hardware.
- A new training revolution is possible. It can pay for itself if structural problems are solved.
- Adversaries could use a new training revolution against us, but so far have been constrained by cost and cultural impediments.

The study of this task force not only confirms these findings, but also concludes that the potential exists to use new technologies in ways that

allow rapid development of and experimentation with new doctrine and operational concepts. The task force believes that rapid development and experimentation can lead to significant improvements in the effectiveness of U.S. armed forces, and that such improvement is both possible and necessary, given the rapidly expanding operational spectrum facing the U.S. military.

Forces train so that they can respond quickly, confidently, and with total dominance. Forces train to avoid surprises, so that superiority comes not only from technological superiority but also from the fact that, no matter what the situation, they have "seen it before."

The Need for Rapid Development of Tactics

In recent years, U.S. military forces have been experiencing a relentless increase in the tempo of operations. While this change in itself is enough reason to carefully examine the adequacy of training programs and technologies, it is the rapidly expanding variety of operations that places the greatest stress on preparedness. Unconventional operations, such as contingencies, urban operations, and peacekeeping missions, routinely lead U.S. forces into encounters with asymmetric threats. As the recent experiences in Somalia and Kosovo have shown, while the United States has certainly established technological superiority over those who pose asymmetric threats, adversaries are still quite capable and will attempt to use tactics that U.S. forces have not before encountered or trained for. In a nutshell, capable adversaries are not likely to fight by the "rules," and in fact they will learn U.S. rules of engagement and attempt to exploit their knowledge to their best advantage.

The effectiveness of U.S. forces in such situations relies to a significant degree on developing the organizational structure and supporting technology to allow for timely and accurate decision making. Advancements in communications technology and military structure, leading ultimately to a working and effective C4ISR capability, are essential ingredients in any strategy for improving decision making. But, ultimately, it is the soldier on the ground or in the cockpit who will face new or unfamiliar situations and will have to rely on superior training to make the right decisions, and it is the commander who must have access to a wider range of operational concepts than ever before. One implication of this circumstance is that the "soldier in the foxhole" increasingly must be trusted to make decisions and take actions. This suggests the need for a flattening of organizational hierarchies, which can lead to greater agility,

as well as the empowerment of people with exceptional abilities to make a real difference.

Indeed, the flexibility and inventiveness of U.S. forces is admirable. But analyses of DoD processes reveal that innovations happen primarily in times of war. One must ask the question: is it possible to create, during peacetime, the constant competitive pressure that leads to rapid innovation? Rapid peacetime development of new operational concepts and even new doctrine would allow substantial benefits in training and readiness, as detailed in previous DSB studies. And while U.S. forces have been able to adapt their operations in time to be effective in Afghanistan, other experiences (such as in Somalia) show that surprises do occur and can have disastrous consequences.

During the course of its study of this topic, the task force made the following observations:

- Technology barriers exist today that, broadly speaking, can be referred to as the "C4ISR problem." However, timely and accurate decision-making is not just a C4ISR problem, but also a problem of overly deep and complicated organizational hierarchies. The most effective way to shorten decision cycles may be to exploit superior training and technology, thereby allowing some key decisions to be made locally.
- Training superiority is a viable and necessary concept, and increasingly so, given the trends in operational tempo and variety. Asymmetric threats are more likely to lead to unconventional and "surprising" situations unless the spectrum of training situations is widened dramatically.
- Peacetime doctrine and operational concept development processes are centralized, hierarchical, and time-insensitive. Innovations seem to occur mainly during the competitive pressure of wartime, which does not allow time for training or for experimentation. Mechanisms for creating competitive pressure during peacetime may provide the impetus for continuous innovation in concept development.

The task force believes that new technologies and, importantly, new mindsets, are available that have the potential of creating constant competitive pressure within U.S. military organizations, leading to a culture of constant experimentation, training, and rapid innovation in tactics and operational concept development. The task force believes that

technologies exist that can, in essence, create a greater range of "past experiences" and thereby create a form of training superiority.

ACHIEVING PRESCIENCE

One of the great frontiers of science today involves the development of a clear understanding of the processes of human cognition. The rise of cognitive science and its relation to psychology, computer science, medicine, and even business has made it clear that tremendous untapped potential exists in almost all areas of human life. Although relatively little is known today, several basic principles that affect training and decision-making are well understood and accepted. First, and perhaps foremost, is that humans tend to perceive what they expect to perceive.

Mindsets tend to be quick to form but highly resistant to change. Even when new information is presented that takes us out of the realm of current operational thinking, the tendency is to assimilate the new inputs into existing images and concepts, as opposed to thinking "out of the box." Indeed, this tendency increases with the ambiguity of the information and the confidence of the actor in the validity of his image. Important changes in a situation can happen so gradually and in such an evolutionary way that they go unnoticed. Ultimately, as one's commitment to an established view increases, so does the tendency to perceive only the expected. In the military context, this phenomenon leads to the tendency to develop training methods, operational concepts, and doctrine that prepare us for the "last war" instead of the next one.

While changing these characteristics of human nature may not be possible, there are in fact well-understood strategies that organizations use to avoid turning these tendencies into liabilities. One basic approach is to create a culture of continuous competitive pressure. Macroeconomic studies of large organizations show that the pace of innovation increases dramatically during times of intense competitive stress. By creating such a culture, organizations seek to harness the power of collective intelligence, since successful competition requires the empowerment of all its members in the innovation process.

Commercial enterprises have long recognized the importance of this strategy, and this recognition has led generally to flatter, more lateral organizational structures. In recent years, these ideas have been married with Internet-based technologies in an attempt to empower and access the collective intelligence of, potentially, millions of people. One simple example can be seen at AskMe.com, which offers companies a way to capture the collective intelligence of its employees. It does so by providing

a kind of corporate clearinghouse of local experts, organized according to key relevant topics (everything from how to analyze the latest market trends for the company's key markets to advice on the best local places for a quick low-calorie lunch), and then creating incentives for experts to provide high-quality answers to questions for other members of the company. What is essential here is that the web technology creates highly efficient and empowering channels of communication, in an attempt to realize the potential benefits of Metcalf's Law.[28] This approach is in contrast to creating central "knowledge management" repositories without creating any collaborative structures.

It is natural to ask whether such collaborative technologies can be brought to bear in improving the DoD's business practices. But a more fundamental scientific question is whether large-scale collaborative technologies can help support a revolution in training and development of new operational concepts. This report suggests that the answer may very well be "yes." Moreover, the technology of massive multiplayer environments may provide the key starting point for such a development.

MASSIVE MULTIPLAYER WAR GAMING

One of the healthiest commercial sectors in the area of information technology is online entertainment or, to put it more simply, computer games, as described early in this chapter. DoD has made substantial investments in modeling and simulation technologies, many of which lie at the foundation of computer games, and this investment has increased steadily as the technology has resulted in clearer and more immediate benefits.

Operations such as the Defense Modeling and Simulation Office, and programs such as JSIM, have interacted in important ways with the online entertainment industry. This interaction has happened both in smaller, focused projects, as well as in larger initiatives such as those embodied by the Institute for Creative Technologies, a joint venture between the U.S. Army and the University of Southern California. Indeed, as a recent report by the National Research Council states, "modeling and simulation technology now provides a low-cost means of conducting joint training exercises, evaluating new doctrine and tactics, and studying the effectiveness of new weapons systems. Both the entertainment industry and DoD are aggressively pursuing development of distributed simulation

[28] Metcalfe's Law states that the usefulness, or utility, of a network equals the square of the number of users.

systems that can support Internet-based games and large-scale training exercises."

The area of most rapid growth and intensive investment by online entertainment companies is one about which adults over the age of 22 have virtually no knowledge: massive multiplayer virtual environments (see Figure 3-7). MMP games make use of the Internet and advanced server technologies to create massive virtual environments in which tens of thousands of players participate simultaneously. In fact, MMP games often follow the trend towards network-based collaboration by providing ways for players to create and contribute new technologies, new virtual spaces, and new tactics for use by the entire community of players.

Figure 3-7. Screen Shots of Some of the More Popular Computer Game Software

There are two essential aspects of MMP games. First, by mixing synthetic players with human players, the depth and challenge of the game play can be heightened. Indeed, within the U.S. government, the importance of multiple human players in simulation-based training is already recognized in developments such as Distributed Mission Training, for much the same reasons that the concept of "red teams" in live

exercises has shown such great value. Interestingly, off-the-shelf technology has advanced to the point that some agencies are able to make use of commercial products as serious training tools. For example, the U.S. Secret Service has used the game Rogue Spear, by Red Storm Entertainment, for training of the presidential protection detail.

Second, in the environment in many MMP games, the incentive of peer respect (which often leads to "promotion in the field") causes players to cooperate and collaborate in forming highly organized societies. This collaboration also leads to the rapid dissemination of new tactics, as well as the development and distribution of new technologies.

Special Opportunity: Peer-to-Peer War Gaming

The possibility that the technologies and concepts underlying computer games might have applications to training, experimentation, and tactics evolution is not lost on the DoD. While much of its investment thus far has been in the core physical modeling and high-fidelity simulation aspects of training systems, some developments along the lines of networked simulation have also been conducted. What has gone largely unexplored, however, is the rising trend towards massive multiplayer gaming, and the possibility that the observed emergent behaviors, accelerated evolution of new ideas, and rapid dissemination of new tactics can be achieved in a practical way for the military.

This study suggests that MMP virtual environments must be investigated thoroughly for their potential to provide prompt joint and service doctrine and concept improvements and evolution, with extensive field participation in their derivation and refinement. If realized, this process would be in contrast to today's peacetime processes for development of doctrine and operational concepts, which are centralized, hierarchical, and time insensitive—and thus slow to mature.

The potential benefits suggest that the DoD should undertake the development or acquisition (and modification) of a toolkit for creating MMP virtual environments, to support on the order of two million uniformed military personnel, both in CONUS and overseas, in exploration and unrestricted play. A collection of MMP environments should be created to provide 24/7/365 availability to Joint Experimentation for the Combatant Commanders, National Training Center, Red Flag, and Fleet Ex-like activities. The goal should be to create peer-to-peer wargames that broaden and flatten access to the best and most innovative thought. Furthermore, these MMP environments should seek to

create continuous, intensive, competitive pressure by facilitating play with many different adversaries and adversarial rules of engagement.

Beyond the network security, server technology, and simulation methodologies involved, additional novel S&T challenges must be overcome. A method needs to be developed for extracting emergent behaviors to discover new doctrine and concepts, particularly in environments in which hierarchy does not necessarily rule, and the primary mode of interaction is through informal (and possibly even unrestricted) "play." A second significant challenge is how to identify, capture, and validate the "winning" concepts and ideas, as well as how to discover unusually talented people. Finally, some cultural barriers may need to be overcome if the notion of MMP environments is to become an element of military training. Today, the average 18-year-old male has over 1,500 hours of video gaming experience (on par with fighter-pilot training hours). The challenge is to exploit and match this level of experience in future training and experimentation systems.

RECOMMENDATIONS

Recommendation: The DoD should undertake a comprehensive investigation into the development and use of massive multiplayer virtual environments for training, doctrine, and concept development and experimentation. The Joint Warfare Center and the European Command (EUCOM) Warrior Preparation Center should serve as "Concept-Testing Masters," in order to provide incentive for participation in the games and to provide deployment and system administration of the game server systems.

DARPA should serve as the technical arm of this research, in part by acting as the primary interface to the video gaming community, and also by commissioning the development of specific MMP gaming engines that would be suitable for military applications. DARPA should also enable basic research on automatic analysis of emergent behaviors in MMP games, with an eye towards extracting not only new operational concepts but also the "3σ" talents in the Joint Warfare Center and EUCOM.

The DoD should invest $75M over the current future years defense plan, with clear metrics used to assess progress. Concrete metrics could include the breadth and numbers of players involved, the numbers of concepts tested, results from critiques and analyses of virtual experiments, and field acceptance of the extracted insights and results.

In 18 months, a tool based on off-the-shelf gaming engines that allows rapid development of relatively small (10^5) MMP environments should be demonstrated. In three years, a dedicated DoD concept exploration system should be produced, which supports the development of multiple, significant military MMP environments. In five years, DoD should have multiple MMP environments running, each with 10^5-10^6 players continuously participating, and with automatic vetting of emergent behaviors.

THE REALITY DIAL

Already in some of today's emerging systems and platforms there is a blurring of the line between the simulator and the actual vehicle. This similarity is particularly true of unmanned aerial vehicles in which the training simulator is essentially identical to the actual flight-control system. In essence, remotely controlled systems lead naturally to the idea of moving seamlessly from the "virtual" to the "real," a concept that this report refers to as the "reality dial." On the virtual end of the dial, is pure simulation, supporting exploration in an essentially free-form and unrestricted manner. Towards the other end of the dial, is experimentation, and then training, and, ultimately, control of actual unmanned systems. Indeed, as unmanned systems become more prevalent, and the fidelity of the simulation technology used for training continues to improve, the question of who and how many people will remotely control our future forces emerges—a topic discussed in Appendix G.

10X HUMAN WARRIOR: ENHANCING HUMAN PERFORMANCE

Medical advances ranging from complex organ transplantation, to artificial cochlea, to implanted insulin pumps, have permitted humans to live longer and better lives. Indeed, the history of advances in bionics and related medicine date back hundreds of years to the first iron prosthetic hand with flexible finger joints in 1504, and have now progressed through discoveries that today permit vision to be restored with a plastic contact lens, age-eroded hips to be renewed with new artificial joints, and the function of lost limbs to be recovered with tendon- or nerve-controlled prostheses. The February 8, 2002 issue of *Science*, entitled "Bodybuilding:

The Bionic Human," chronicles this amazing progress over hundreds of years. Examples appear in Table 3-1.

Table 3-1. History of "Bodybuilding"

Year	Advance
1597	Reconstruction of the nose by tissue grafting
1682	Repair of human skull with dog skull bone
1888	First reports on use of contact lenses to correct vision
1905 & 1906	First reports of corneal transplants
1957	First successful cochlear implant developed
1972	Testing of modern design steel/polymer hip joint
1986	First successful double lung transplant
2000	Implantation of a prototype artificial pancreas

The articles also describe current research that will shape the future:

"From tendons to bladders, bioengineers are manufacturing 'ready-to-wear' designer tissues in the laboratory. They are coaxing cells to assemble into three-dimensional structures on biodegradable scaffolds that can be implanted in patients at sites of tissue injury… Sophisticated microelectronics for signal processing are bringing the dream of merging man and machines closer to reality."[29] The use of medical implants, transplantation, and artificial devices is indeed a scientific and technological megatrend.

Nearly all of the examples above involve restoration of function, not enhancement of function. While advantages might be realized by military personnel by capitalizing on such medical breakthroughs, the understanding and progress made in this area leads naturally to questions regarding their potential use for enhancing human function. In the near term, improvements in selection and training are possible. In the far term, the task force envisions a time when cochlear implants might extend the range of human hearing, or perhaps when an artificial retina would permit a human to see in the infrared.

These concepts raise profound ethical questions. Indeed, such concerns have become pervasive, among experts and laypeople alike, as advances such as genetic engineering and implanted microelectronic devices open up entirely new possibilities. Regardless, the task force argues that the needs of an aging population will ensure continued progress despite ethical debates, and as has long been the case, not everyone will share the same values about "fair play." A prime example is presented by the risky, yet prevalent, use of performance-enhancing drugs in sporting events.

[29] *Science*, Vol 295, No 5557, pp 917-1180. 8 February 2002.

> Doping scandals have become an almost routine part of modern sporting competitions, including the Olympics. But many sports scientists warn that performance-enhancing drugs may be a thing of the past when it comes to illicit ways to win. Scientists on the forefront of genetic manipulation predict that in as little as five to 15 years, athletes may be using genetic engineering to get the edge over their opponents.[30]

The ethical questions posed by the ability to enhance human performance will need to be addressed. However, an intense desire to push the envelope combined with an increasing spectrum of possibilities for enhancing human performance makes doing so inevitable. In the future, genetic screening, genetic manipulation, use of advanced "doping agents" with highly targeted outcomes, and other more exotic tools such as bionic interfaces are likely to be used to dramatically improve training outcomes. Tasks with stressing performance requirements will necessarily drive the trend; the DoD would be shortsighted to ignore the role of such future capabilities in warfighting.

Opportunities for Warfighter Effectiveness, Enhancing Human Performance

The reality of modern warfare is that warfighters face around-the-clock demands, at greatly increased operational tempo, using increasingly sophisticated systems. Many potential opportunities exist for improving warfighter effectiveness by enhancing human performance. Table 3-2 highlights some of the myriad objectives that might be sought through techniques to increase the normal functionality of humans. This report focuses on only a few.

Table 3-2. Objectives for increasing human performance in warfighting

Increase	Decrease/Regulate
Strength	Sleep requirements
Reflexes	Caloric requirements
Alertness	Fatigue
Memory	Perception of pain
Senses (hearing/vision)	Adverse stress effects
Cognitive capabilities	Motion sickness
Profiling*	Serious injuries*
Training*	(* Indicates nearer term capability)

30 CNN.com news report, "Genetic enhancements may be on horizon for athletes", February 20, 2002.

New opportunities in cognitive psychology, cell signaling and regulation, advanced therapies, sensors and implants, artificial organs, and drugs have laid the scientific foundation for achieving these objectives. Breakthroughs in genetic screening techniques will make it possible to identify individual genetic variances that might be correlated with cognitive abilities, reflexes, cardiovascular endurance, strength, and other features relevant to warfighting. The ability to recognize such correlations will require the creation of genetic databases. While such information may be beyond the social tolerance level for the general population, it should be considered for active-duty military personnel.

Notably, assessments of physical and psychological performance under challenging conditions (flight training, SEAL selection) are currently used to identify the individuals best suited for these roles. Such screening techniques are an integral part of the selection of personnel for elite forces, but they are costly and time consuming. Given this history, the use of tools such as genetic screening or other quantitative biotechnology-based techniques as part of the selection and specialization process over a wider portion of the military population should be acceptable. Such tools might also create collateral benefits in reducing "wash out" and the concomitant psychological damage. It should, of course, be recognized that not all differences in performance will be attributable to genetic differences; however, some will clearly be linked.

As an example of the types of performance differentials that may be observed through the collection of genetic data, consider that sprint athletes have 75% more fast-twitch muscle fibers than distance runners, who have 75% more slow-twitch fibers. Fiber-type composition is mostly a product of heredity, and while training may alter it slightly, it cannot change the baseline muscle composition sufficiently to result in the high percentage of fast-twitch fibers needed in elite sprinters. Canadian scientists, Drs. J. Simoneau and C. Bouchard, have estimated that 40 percent of the phenotypic variance of fiber type is due to environmental influences (i.e., exercise) while 45 percent is associated with genetic factors. (The remaining 15 percent is due to sampling error.) Thus all people are born with a given athletic potential. Training will maximize that potential, but if you are not born with world-class running potential, you will never become a world-class sprinter or distance runner. This idea is true at a basic level for individual traits that affect both physical and mental capabilities. Thus, training can modulate innate differences, but those differences cannot be eliminated. The primary objective, therefore, of genetic databases and screening should be to reveal individual

capabilities so as to enhance performance further through proper selection and training.

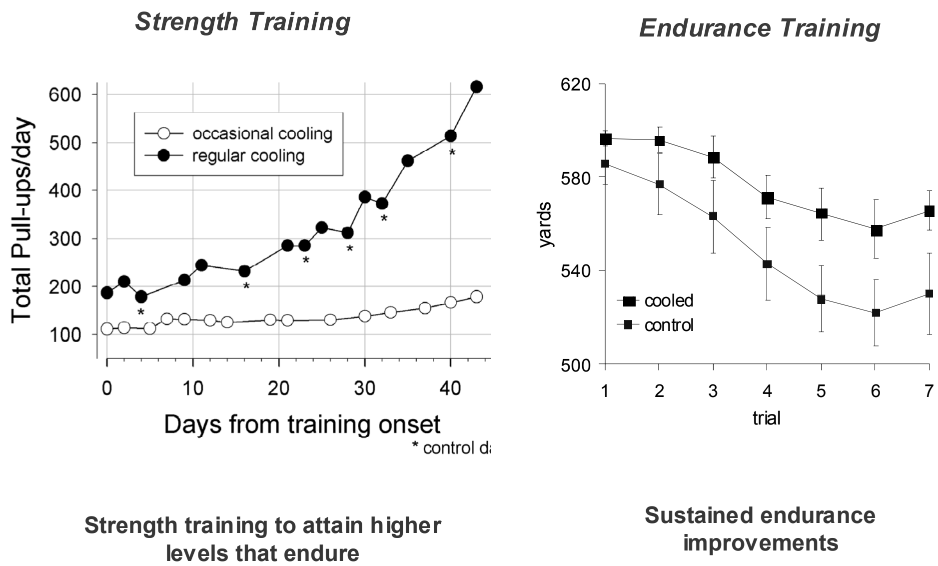
Recent advances in medical science also aid the optimization of performance. As scientists better understand the basic elements of human physiology, dramatic improvements can be achieved in training. Figure 3-6 shows the impact of controlling core body temperature on strength and endurance training.

Figure 3-6a shows the conditioning progress of a body builder during twelve weeks of controlled training runs. A control run consisted of repeated sets of pull-ups to exhaustion with three-minute rests. In each case, the numbers represent the total number of pull-ups completed in 14 sets. The bottom curve, labeled “occasional cooling,” illustrates the first six weeks of progress in strength training made when the test subject’s core body temperature was reduced after the ninth set of pull-ups. During the second six weeks, represented by the upper curve labeled “regular cooling,” the subject received cooling after every other set of pull-ups. Starred days are control days with no cooling. Note that improvements only occurred during cooling days in both six-week periods. When regular cooling was used, the test subject’s strength endurance increased three-fold. Notably, these results were repeated in reverse order with a group of three wrestlers who showed steady improvements with core body temperature cooling and reached a plateau when regular cooling was stopped.

Figure 3-6b shows the impact of such cooling on endurance. In this experiment, football players were subjected to repeated two-minute sprints with three-minute rest periods. The test subjects in the “cooled” category received between one and one and one-half minutes of cooling between sprints. Note the difference in the performance decrement in successive sprints. As these experimental results indicate, improvements in strength and endurance can be enhanced through an understanding of the influence of body core temperature on performance.

These examples indicate that significant improvements in human performance can be expected and realized by adhering to the following credo: “Select for natural abilities, then optimize performance.”

Figure 3-6. ***The impact of controlling core body temperature on a) strength and (b) endurance training.***



Such improvements are but the beginning. Bionic devices that permit extended-range hearing or multi-wavelength vision will be within grasp in the next decade. The ability to interface directly with the body over extended time periods as well as the ability to process additional cognitive inputs will determine the pace at which such capabilities emerge. At the same time, the risk associated with such implants will be reduced because of the growing experience with similar devices used to restore function, and the risk that the United States will face warfighting adversaries who have chosen to capitalize on such enhancements will be increased.

Recommendation: The Department of Defense should undertake an exploratory, socially, and ethically responsible program to investigate technologies and techniques for enhancing human performance. In the near term, the program should focus on the enhancements of performance made possible through better selection, screening, and training techniques. Future aspects of the program should be focused on enhancement through sensors and implants, drugs, cognitive psychology, cell signaling and regulation, and advanced therapies, among others.

Programs to advance such technologies and techniques for enhancing warfighter performance should be increased by $30 million per year.

BASIC SCIENCE INVESTMENTS: NANO AND QUANTUM TECHNOLOGY

Two areas of research in technology portend radical changes in the future technology landscape; they are nanotechnology and quantum information systems. At this stage of maturation, it is not possible to determine what specific future military capabilities will be made possible as a result of investments in these technology areas. At the same time, it seems clear to this task force that a failure to embrace these areas of widespread scientific pursuit could lead to unsettling technical surprises. The United States must therefore play a major role in the development of these technologies and creates the talent pool necessary to exploit developments in these areas. The investment in basic research necessary is modest. The potential payoff is disproportionately large.

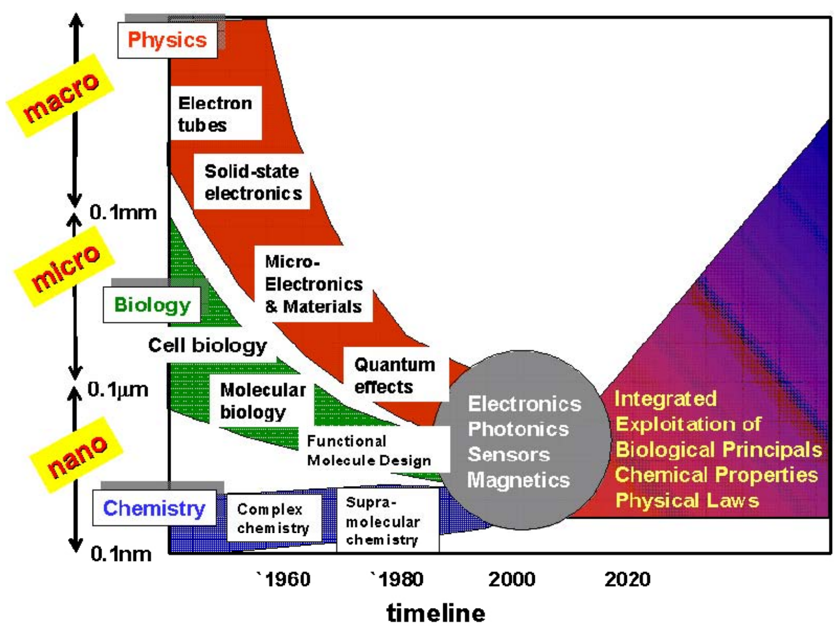
NANOTECHNOLOGY—WHAT IS IT, AND WHY SHOULD THE DOD CARE?

Over the past two years, the scientific and industrial communities have embraced nanotechnology as perhaps the most important upcoming field in science, with the potential to revolutionize virtually every modern technology, from materials to information processing to medicine. At the same time, the actual definition of nanotechnology has remained vague—especially to laypersons. Nanotechnology does, in fact, mean many things to many people, because it represents a broad area of science. Some appreciation of the breadth of nanotechnology, and why it is difficult to define explicitly, can be gained by considering Figure 3-8.

Here the various fundamental fields of science—physics, chemistry, and biology—are charted as a function of time versus an unusual axis, namely the characteristic length scale that represented the frontier of that field at a given time. For physics and biology, that scale has decreased with time, although for different reasons. The frontiers of solid-state physics have evolved from the development of a quantitative understanding of bulk materials, such as superconductors and semiconductors, to the current frontier of trying to understand and control

the quantum mechanical behavior of nanoscale structures. This evolution of physics has fed into and benefited from the development of photo-lithography and other top-down fabrication approaches. Biology, on the other hand, moved from the phenomenology of cell biology to the more exact science of molecular biology and now into the predictive and rational molecular design of therapeutics. Finally, chemistry has moved from the simplicity of small molecules to the complex character of macromolecules and supramolecular assemblies. All three of these fields are now converging on the common (nano)length scale of 1 to 100 nanometers (nm's). For reference, a typical chemical bond is about 0.1 nm in length, a protein or other large biological macromolecule is about 5-10 nm across, and a transistor in a state-of-the-art Pentium IV chip has components that are just over 100 nm in size.

Figure 3-8. The time-evolution of the various physical sciences, plotted as a function of the length scale that represented the frontier of research in those fields.



The convergence of the fundamental scientific disciplines onto the nanometer-length scale implies several things, including the following:

- A bottom-up, or biologically-inspired, manufacturing approach will be coupled with the traditional top-down fabrication that is utilized in nearly all products made

today. This bottom-up manufacturing approach is a common signature of many nanotechnologies.

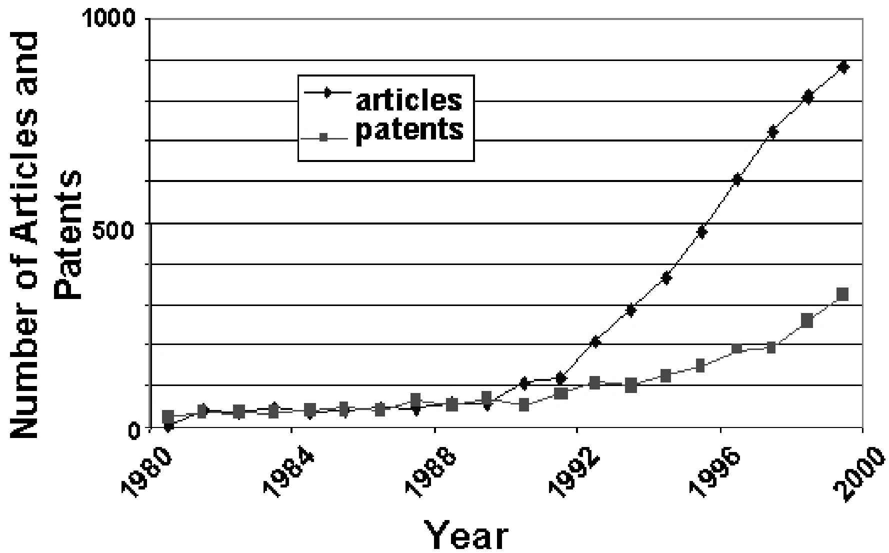
- The functional complexity that is characteristic of biological systems may be harnessed for applications as diverse as communications, medicine, or structural materials.
- The fundamental length scale of manufacturing complexity is one in which quantum mechanical interactions and chemical interactions may dominate.

For the DoD, nanotechnology will provide the preferred platform for future photonics, electronics, magnetics, and sensing devices. It will provide the pathway for multifunctional materials, such as ultra-strong, lightweight materials capable of active camouflage and stealth and even, perhaps, self-healing. It will provide for devices that are capable of ultra-secure communications, as well as rapid code-breaking systems. It will eventually be the enabling technology for many advanced versions of the grand challenges discussed in this report, such as “Bug-to-drug in 24 hours,” biological warfare defense, the “10× human warrior,” or the sensor nerve networks discussed in “No place to hide.” Finally, nanotechnologies tend to be highly energy efficient, thereby reducing the tax on fuel and battery life, which has obvious direct benefits for the warfighter.

While the potential and promise of nanotechnology are tremendous, a concerted, long-term research effort is required to bring it to fruition. One way to gauge the time required for an emerging technology to generate commercial products is to look at the historical chronicle of scientific publications and patents in that field. Such a chronicle is presented in Figure 3-9. Perhaps the most similar previous technological revolution was in biotechnology—a field that has developed into a healthy (but still very young) industry just within the past few years. By comparison, Figure 3-9 implies that a healthy nanotechnology industry may exist by 2020.

In the remainder of this section, a timeline is presented for the development of nanotechnology, highlighted by a few specific examples of products that are likely to emerge. Following is a discussion on the scope of the worldwide corporate and governmental research efforts in nano-technology. In many of the most critical applications of nanotechnology, the United States is not in the lead in either funding or research results. Finally, a discussion is presented on how DoD investments in nanotechnology can be best leveraged.

Figure 3-9. A chart of nanotechnology-related scientific articles and patents indicates that this field is where biotechnology was 20 years ago.



The Timeline for Nanotechnology

As stated above, one objection that people have to discussion of nanotechnology is that it appears to be too broad, encompassing almost everything. Imagine if top-down fabrication were being proposed for the first time. Theorists could envision carving out spearheads, and eventually getting to the integrated circuit. Nanotechnology, with its accompanying bottom-up fabrication, is well described by this analogy. One way to break down the development of nanotechnology is to categorize it according to the difficulty in manufacture, starting with randomly dispersed nanopowders. Table 3-3 represents such a breakdown. This list is far from complete, and, becomes increasingly vague as the time-horizon lengthens.

Table 3-3. The Various Stages of Nanotechnology

Timeline to Product	***The Nanocomponent is Passive.*** For these applications, the nanocomponent lends a materials property, such as strength, thermal conductivity, etc., to the final product.	
	0 length scales controlled, single-component material	**Nanopowders** *Many existing applications in reprography, catalysis, combustion initiators, paints, etc.*
	0 length scales controlled, multi-component material	**Particle / polymer dispersions** *Existing applications in tires, rubber materials; future applications in lightweight, structural materials such as the body panels of cars, fuel cells, etc.*
	1 length scale controlled	**Mesoporous materials** *Existing applications in toxic waste remediation; catalysts; magnetoresistive materials; Future applications in photonics, paints, camouflage; lightweight, high temp structural materials*
	Multiple length scales controlled	**Multifunctional materials – e.g. structural + thermal conductivity + electrical conductivity, etc.** *A few applications exist, including very low threshold lasers; cheap but low-efficiency photovoltaics; Future applications are many, including thermoelectrics; highly efficient white lighting.* *Most current long-term industrial R&D by chemical companies is focused here.*
	The Nanocomponent is Active. For these applications, the nanocomponent is the switch, sensor, transducer, quantum bit, etc. These applications are significantly more demanding, and generally longer term.	
	Active, non-interacting nano-components	**Conducting nanowires, single atom dopants, nanoresonators** *Quantum cryptography, chemical and bio sensors and detectors, ultra-high frequency communications.* *Mostly academic work, small corporate investment – chiefly through startups. Many laboratory demonstrations, 5-8 years out for first few commercial products).*
	Active, interacting nanocomponents (implies control over multiple length scales	*Quantum information storage, molecular memories, molecular medical therapeutics, etc., high amplitude piezo-chemical, piezo-optical, piezo-electronic materials (i.e. shape-controllable materials)* *10-20 years out, largely academic investments, a few laboratory demonstrations exist that have technological relevance)*
Far Term	***Active, coherently interacting, time-evolving nano-components***	*Quantum computing* *(largely academic investments, a very small amount of industrial research (est. <$3M); a couple of scientifically (not technologically) relevant demonstrations exist).*

Corporate and International (Non-U.S.) Investments in Nanotechnology

The worldwide corporate investment in nanoscience is estimated to be greater than $1 billion per year. This investment is dominated by R&D efforts in certain existing nanotechnology products such as nanopowders, giant magnetoresistive read heads for magnetic storage devices, and nanofluidics for inkjets and pharmaceutical screening technologies. Some of these products are new, while others have been around for some time. A smaller fraction of these dollars are invested in highly targeted applications of nanotechnology such as certain high-end nanomaterials, or biomolecular sensor technologies, and this work is largely being carried out in small, venture capital (VC)-funded start-ups.

The smallest fraction of the total corporate investment (probably less than $50 million per year worldwide) is devoted to high-risk, high-yield technologies such as molecular and nanoelectronics and quantum information technologies. Out of this relatively small pot, non-quantum nanoelectronics receives the lion's share of the funding. Not included in this estimate are the R&D dollars spent on scaling silicon-based technologies to nanometer dimensions, as that research is focused on extending current and maturing technologies, not on developing fundamentally new and potentially disruptive ones. A few specific examples of corporate R&D efforts in nanotechnology are given in Table 3-4. All dollar figures are estimates, but were based on conversations with key company employees.

Worldwide Government Investments in Nanotechnology

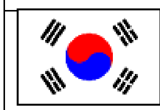
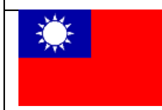
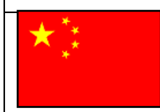
The overall non-U.S. worldwide government investment in nanotechnology, for 2001-02, is thought to be in the $850M range, according to Dr. M.C. Roco, Chair of the National Science and Technology Council Subcommittee on Nanoscale Science, Engineering and Technology. This investment is split almost evenly between the European Union and Asia. Exact numbers for participating countries are difficult generate—especially since many of the national nanotechnology initiatives are just now accelerating. Table 3-5 details some of the various Asian programs, several of which are planned in the range of $100 to $200 million over a period of the next three to five years. The total Asian investment in nanotechnology R&D is likely between $350 and $450 million per year, with Japan the major investor. However, significant

efforts are ongoing in nearly all countries around the globe that have or are developing a technology base.

Table 3-4. Some U.S. Corporate Investments in NanoTech R&D

Company	Fundamental research; note	Supporting R&D	$$	Source
hp invent *Hewlett Packard*	*Molecular electronics; nano materials*	*Nanofluidics (advanced inkjet technology)*	*$5M/yr Basic >$50M/yr applied*	*Stan Williams; HP Labs Principal Lab Scientist & HP Fellow*
QUANTUM DOT *Quantum Dot Corp.*	*These are typical nanotech start-up companies. They are premised on an emerging technology with broad and expanding applications, but are initially targeted at niche markets.*	*Semiconductor quantum dot biological labeling; advanced materials*	*$60M VC capital over 3 yrs (advanced to Stage II)*	*Paul Alivisatos; founding scientist, Quantum Dot Corp.*
Carbon Nanotechnologies Incorporated		*Single walled carbon nanotubes for materials (incl. DoD) applications*	*$15-20M VC funding (Stage I)*	*Rick Smalley, founding scientist, CNI*
NanoSys		*Nano and molecular electronics; sensors*	*$15-20M VC funding (Stage I)*	*Larry Bock, CW Group & Founder NanoSys*
MOTOROLA North America Region	*Nano & molecular electronics; nano-biotech*	*?*	*$8M/year (15-20 people)*	*Herb Goronkin, Motorola VP*
IBM	*Nanotech IT incl. Molecular elect.; quantum IT*	*Nanomagnetics including magnetoresistives*	*$10M/year Basic; >$50M/yr applied*	*size of IBM nano R&D effort based on conversations with IBM research staff members.*

Table 3-5. Some Asian Governmental Investments in NanoTech R&D

Country	Research Focus	$$	Source
 *Singapore*	*R&D very connected to industrial needs; not much high-risk work*	*Scaling to Tens of $M's /year*	*Mr. Ming K. Teo, Chair, Singapore Econ. Dev. Board*
 *S. Korea*	*Basic and applied investments; leveraged by industry. Three major centers in Taiwan; Two(?) major centers in South Korea.*	*Scaling to >$30M/yr*	*Dr. Gibs Song, President, Samsung Advanced Institute of Technology*
 *Taiwan*		*Scaling to >$40M/yr*	*Dr. Cho-Ho Wei, Chairman, National Science Council, Republic of China*
 *China*	*Basic nanomaterials R&D is a major strength*	*$$ figures not available but a marked increase in high quality nanotech papers over the past few years implies a significant national investment.*	

How Should the DoD Invest in Nanotechnology?

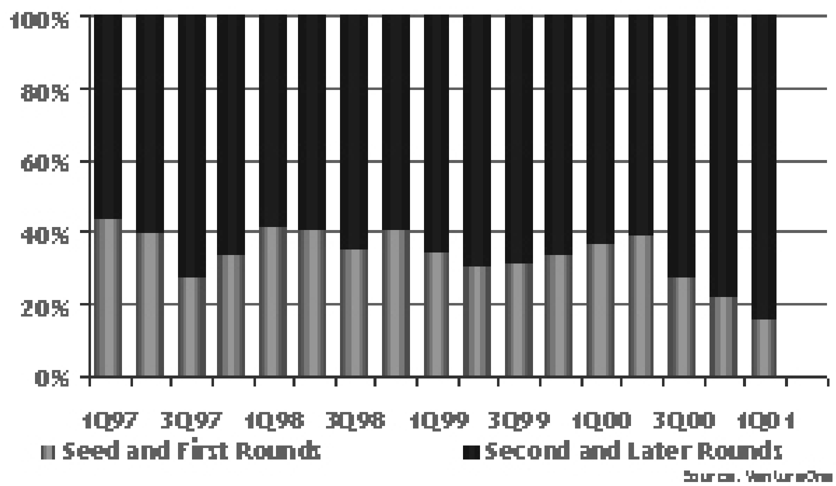
Given an appropriate long-term investment, nanotechnology is likely to lead to very significant, even revolutionary, changes in products for both the military and the civilian sector. However, any funding or business model for promoting nanotechnology development must account for the following:

- Some nanotechnologies may provide pathways for the incremental improvement of existing technologies, and near-term applications of nanotechnology will arise from these improvements. Most applications, however, will rely on quite different manufacturing approaches and will produce very different products than what currently exist.
- Nanotechnologies will initially find their foothold in niche markets.
- Even for a niche-market application, the vast majority of nanotechnologies will require long-term and sustained investment.

These considerations have several implications. First, large companies are unlikely to invest serious resources into nanotechnology development. The implications for start-up companies are perhaps even more severe,

especially given the recent economic downturn. Start-up companies are typically funded through venture capital. After reaching historic highs, the return on venture fund investment has been dropping steadily over the past two years, and in the most recent quarters, it has actually been negative. Private-sector money has thus been pushed into funding later-stage, low-risk companies, as indicated in Figure 3-10. This figure describes where private funds are being invested, and shows that long-term, early-state investments, such as are required for most nanotechnologies, are becoming increasingly disfavored (light bars) over short-term, low-risk investments.

Figure 3-6. Comparison of Early and Later-State Company Mix



The DoD can play three key roles in helping to bring nanotechnology to the marketplace:

1. The DoD can provide a steady level of funding for those nanotechnologies that will most directly affect the warfighter. If fundamental scientific issues stand between a technology and the market place, neither large companies nor venture capital firms are likely to pursue them.
2. The DoD can promote a strong dialogue between the scientists working in the various areas of nanotechnology, and the military personnel responsible for maintaining national security. Such communication

is not always done very well. Given the recent terrorist attacks of September 11, scientists working on nanotechnology are likely to be more than willing to steer their research towards the needs of the DoD, provided that those needs are well elucidated.

3. The DoD can be the initial customer for many nanotechnology products, thereby providing the niche market that can drive early product development. It will thus catalyze the influx of venture capital and corporate funding into nanotechnology, and will leverage DoD investments in this field. This approach is historically the way that the DoD has done business. However, the Department is (appropriately) rethinking this approach with respect to many DoD acquisitions. It is, the task force believes, still valid for such high-risk, high-yield areas as nanotechnology.

QUANTUM INFORMATION SYSTEMS

The second area of basic science in which the DoD should invest is quantum information systems. Like nanotechnology, the potential effects of advances in quantum information technology promise to be far-reaching. This section provides a short overview of this field, in which dramatic breakthroughs have occurred in recent years. The task force argues that this scientific area is one where national security requires that the United States be first in discovery, first in understanding the practical implications for communications and computing especially, and first in exploitation of the technology. The investment dollars are, at this stage, relatively few. Tens of millions of dollars per year would be sufficient, in the opinion of the task force, to ensure that the most aggressive basic research activities are conducted in the United States.

Background

The semiconductor devices that enable today's computation and communications continue to evolve rapidly along a path remarkably predicted by Moore's Law. Microprocessor speeds are being increased by creating devices of ever smaller lateral dimension (today they are 100 nm) and by introducing new materials with higher electron mobilities (e.g., silicon germanium alloys). No physical barrier appears to exist to impede the reduction of device dimensions to the 10nm range. Novel "molecular" electronics concepts are being explored for building devices in the sub-10-

mn range. They hold significant promise, but many challenges will need to be overcome, including the need to establish reliable interconnectivity.

All of these devices rely upon the transfer of charge to accomplish classical computation. The enormous civilian demand for these high-performance-computing devices will drive commercial investments in these technologies until about 2020 when Moore's Law reaches the atomic limit. Until then, the DoD will be able to seek asymmetric advantage from its proximity to the developers of the newest technologies. It should also work to catalyze the production of devices of military importance (e.g., nonvolatile memory and radiation-hardened electronics).

Potential Implications for National Security

Recent developments in quantum physics and computing have created the possibility of a completely different approach to computation and the devices that are used to accomplish it. Quantum information processing offers potentially revolutionary breakthroughs in both communications and computation, including:

- Algorithms for calculations that are impossibly complex for classical computers (today's or any of those envisioned above). Such algorithms could be used to factor large numbers, providing a route to the decryption of previously secure communications.
- The potential of ultra-secure (zero intercept probability) communications.
- Communication bandwidths that exceed (by 100%) those of classical (Shannon) channels.
- Ultra-precise metrology, which will improve GPS precision by a factor of 10^3.

Further investments promise to expand the capabilities of quantum information processing approaches. The algorithmic efforts have been small to this point.

The field's advancement is predicated upon the development of physical realizable qubits.[31] Many schemes have been proposed including photon polarization electron states of trapped ions/atoms, electron or nuclear spin, or magnetic flux state of Josephson junction rings. Two qubit systems have been built using trapped ions, but they are unsuited for

[31] Quantum bits, or qubits (pronounced "cue bits"), are the fundamental elements of a quantum computer.

scale-up. A machine with 100-1000 qubits is envisaged for the applications above. Qubits based upon electron spin (in silicon) may be best for logic. Those involving nuclear spin (also in silicon systems) are the most promising for storage while electron spin systems in III-V semiconductors are likely to be preferred for communications. Recent modest US investments have led to rapid advances in semiconductor-based electron and nuclear spin-based devices. However, these developments are not confined to the United States. Many nations with a history of sustained investment in condensed-matter physics also possess significant, and similarly successful, quantum computing programs.

CONCLUSIONS

In addition to focusing on current needs, the Department of Defense must examine the "megatrends" in today's global technology landscape. These megatrends represent areas of potential explosive growth where new capabilities might arise for the United States military and for its adversaries. Just as importantly, they portend major shifts in the mindset and talents of future warriors. If the DoD does not effectively utilize tools that are available in the global commercial marketplace, it will frustrate and underutilize young military personnel.

Exploitation and develo0ment of opportunities presented by these megatrends requires more than an understanding of the technology—it often requires a change in mindset or a willingness to consider new rules. Failure to recognize or capitalize on opportunities before an adversary does, or dismissal of those opportunities that create some uneasiness, could result in the United States being surprised, perhaps catastrophically.

Further, the vision of industrial leaders and the spending of their research and development organizations determine the path for today's high-tech megatrends. The Department of Defense no longer sets the agenda—indeed, it hasn't for nearly a decade. The Department no longer enjoys a first-tier status in technology development. For this reason, the task force argues that DoD needs a fundamental revitalization of the S&T enterprise.

CHAPTER IV

INVESTMENT STRATEGY

The Department of Defense (DoD) needs to make significant changes to the content and conduct of its science and technology enterprise. Changes are necessary because the processes, practices, and to an increasing extent, content of the S&T enterprise are inadequate to deal with the challenges and opportunities of the new security environment.

In particular, important elements of the new security environment that must be considered include:

1. A few new threats so pernicious that they demand greater attention and resources. Biological warfare is a prime example.
2. Emerging new operational concepts—derived from synergies among joint operations, decision superiority, network-centric operations, effects-based thinking, and rapid decisive operations—with the potential to create revolutionary new military capabilities.
3. Greater uncertainty about the future security environment and the concomitant need to plan more in terms of capabilities rather than to meet "the threat." The S&T enterprise will need to be more nimble and to pay more attention to investment strategies designed to hedge against future uncertainties.
4. A radically different defense-relevant technology base than had existed during the Cold War. This technology base used to be largely government owned or controlled and is now largely commercial, global, and increasingly not well understood by DoD decision makers. No only must DoD better utilize this resource, but it must understand and address its ready availability to potential adversaries.

To meet these challenges and grasp the opportunities presented by the new security environment, the task force identified five course changes to guide the S&T enterprise:

- More aggressive exploration of emerging technologies with yet uncertain military implications—promote discovery.
- Much more focus on the critical enablers of revolutionary military capabilities—promote transformation.
- Much more rapid and timely technology insertion—time matters.

- Creation and consideration of many more options—to deal with greater uncertainty.
- More attention to the technologically feasible and responsive threats—to gain a deeper understanding of how potential adversaries can exploit new technologies.

This brief introduction has identified challenges and opportunities of the new security environment and offered a set of new directions to guide the conduct and content of the S&T enterprise. The remainder of this chapter focuses on two high-leverage areas and makes specific recommendations to move the S&T enterprise in these directions.[32]

The two areas are:

- How to enable S&T activities to promote both much more rapid technology insertion and the transformation of U.S. military capabilities. The task force believes the answer is a greatly expanded use of the spiral development process that integrates S&T with the acquisition and requirements processes.
- How to gain much more understanding about, and access to, the waves of commercial technology.

In addition, this chapter briefly addresses a long-standing concern:

- How to assure the quality of DoD's science and engineering workforce and the relevance of the Department's laboratory system.

The sections covering these three areas are followed by a brief discussion of resource and funding implications. As background, the task force reviewed over 30 prior Defense Science Board studies relevant to S&T investment strategies and show in Table 4-1. Much of the discussion that follows has been presented before by many of these DSBs. However, many of the earlier findings and recommendations have not yet been implemented to the extent envisioned, though they remain sound, relevant and—in the view of the task force—still needed.

[32] This chapter reflects the work of and was prepared by the Investment Strategy Panel of the 2001 DSB Summer Study task force. The panel membership, along with the government advisors and staff who contributed to this effort, is contained in Annex B.

Table 4-1. Prior DSB Studies Relating to Investment Strategies

Tech Base	S&T Programs
• R&D Strategy for 1990s (1990) • Investment for 21st Century Military Superiority (1995) • Tactics and Technology for 21st Century Military Superiority (1996) • Defense S&T for the 21st Century (1998) • Defense Technology Strategies (1999) • Adequacy of DoD S&T Programs (2000)	• Low Observables Technology (1990, 1993) • Joint Advanced Strike Technology Program (1994) • Unique Surveillance Technologies (1995) • Global Positioning System (1995, 1997, 2000) • Breakthrough Technologies (1995) • Combat ID (1996) • ATR (1997) • Underground Facilities (1998)
Transition of Technology	**DoD Labs**
• R&D Strategy for 1990s (1990) • R&D Investment Strategy for the 21st Century (1995) • Defense Technology Strategies (1999)	• Defense Laboratory Management (1994, 2000) • Role of FFRDCs (1995, 1997) • Human Resources (2000)
Commercial Industry Participation	**Access to Commercial Technology**
• Microelectronics Research Facility (1992) • Acquiring Defense Software Commercially (1994, 2000) • Open Systems (1998)	• Globalization and Security (1998) • Technical Capabilities of Non-DoD Providers (2000)
ACTDs	**Acquisition & Procurement**
"Fieldable Prototypes" • R&D Strategy for the 1990s (1990) • R&D Investment Strategy for the 21st Century (1995)	• Defense Acquisition Reform Phases I, II, III, IV, R&D (1993-1999) • Engineering in the Manufacturing Processes (1993) • Modeling and Simulation (1993) • Outsourcing and Privitization (1996) • Investment Strategy for DARPA (1999) • Health of Defense Industry (2000)

EMBED S&T ACTIVITIES WITHIN AN EXPANDED SPIRAL DEVELOPMENT PROCESS

The transformation of DoD's S&T enterprise must be considered in the larger context of the relationship of S&T activities to DoD's requirements and acquisition processes. Two major themes are fundamental to transforming the S&T enterprise

First, S&T activities should be structured to enable transformation of U.S. military capabilities. Transformation occurs when major changes in capabilities enable new ways to fight. Thus, S&T activities should provide not merely incremental improvements but the new operational capabilities and concepts needed to meet the security challenges of the new century.

S&T is a critical enabler of such new capabilities and concepts, but only an enabler. Technology will make the greatest impact when doctrine, organization, training, and the critical human dimensions including, leadership skills, co-evolve with technology and materiel to foster new operational capabilities and concepts. Such co-evolution requires close and iterative interaction between technologists and those who develop military concepts, not a sequential "toss the requirements over the transom" process.

Second, time matters. The Department needs to shorten the time it takes to field new military capabilities for many reasons. DoD faces clever, resourceful adversaries with access to militarily relevant commercial technology. Intelligence capabilities may not be able to provide much advance warning of new threats from a diverse set of state and non-state adversaries. Moreover, protracted acquisition programs are an inefficient use of precious resources. Stretching the duration of programs often precludes the incorporation of more modern technology into systems.

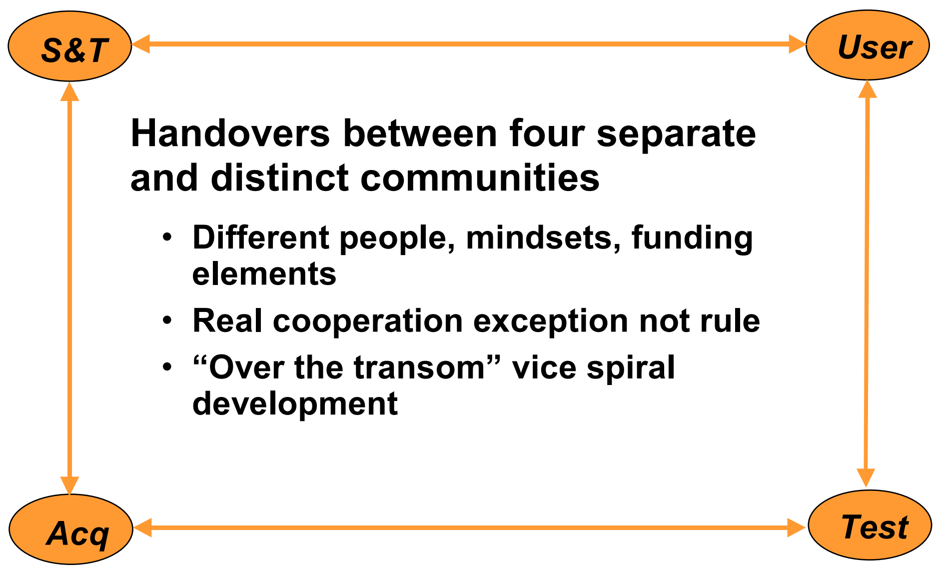
The Department's S&T and acquisition processes need to become more agile, and thus better suited to the greater uncertainty the Department faces. In DoD, the transition time required for advanced technology systems to be made available to forces should be as powerful a driver as "time to market" is in commercial high-technology industries. This is not yet the case.

An effective S&T enterprise should be both opportunistic (technology push) and responsive (demand pull). The once strong ties among S&T providers, system developers, and end-users appear to have been eroding

for quite some time. It is understandable that the S&T base is of marginal significance when system development programs are not driven by efficient use of investment funds, and are allowed to run for one to two decades before producing a useful product. In the absence of "demand pull," the S&T base has become characterized by (1) a lack of direction and focus, (2) less than uniformly high quality in its programs and work, and (3) still inadequate exploitation of commercial products, technology, processes, and expertise.

In addition, a major hurdle to both fostering transformation and shortening transition is to bring together four communities—the user, S&T, acquisition, and test communities—that too often operate independently, as characterized in Figure 4-1.

Figure 4-1. Current DoD Transition of Technology



As an example of the problem, consider the advanced concept technology demonstration. This activity was established almost a decade ago to facilitate rapid transition of mature technology to the field. However, while ACTDs bring together the S&T and user communities, involvement of the acquisition and test communities remains weak. The transition is stretched out beyond the original intent and a system development and demonstration phase is the rule rather than the exception. The "good enough" objective of the ACTD process is often dismissed because of insufficient attention to training, doctrine, spares, and the "ilities."

The Department can resolve the apparent tension between the twin goals of transforming military capability (implying revolutionary capabilities) and shortening the time to get products into the field. The resolution will occur through the widespread and aggressive implementation of the practices of ***spiral development***, a common commercial practice used for development of software and hardware. Spiral development is key to both transformation of forces and transition of technology to the field, and the task force strongly endorses DoD's recent moves toward its implementation. The Under Secretary of Defense for Acquisition, Technology, and Logistics (USD (AT&L)) has institutionalized this approach in directives, and the Vice Chairman, Joint Chiefs of Staff has done so in the requirements process. However, thus far the use of spiral development appears to be more theory than practice, still the exception rather than the norm. Its use needs to be greatly accelerated and expanded.

Spiral development is defined by several characteristics. First, spiral development is a continuous, iterative process linking users, developers, acquirers, and testers. Second, technology and operational options are explored via experiments and advanced concept technology demonstrations. Third, demonstrated technology is rapidly incorporated into "Block 1" systems in the field. Finally, more advanced versions of the technology are deployed in subsequent "blocks" (continuing research and development, deployment, and support processes).

Spiral development offers a means to achieve revolutionary capabilities via evolutionary and disciplined processes. It can lead to exploration and demonstration more options, more rapid fielding of new capabilities, and lower development cost and risks.

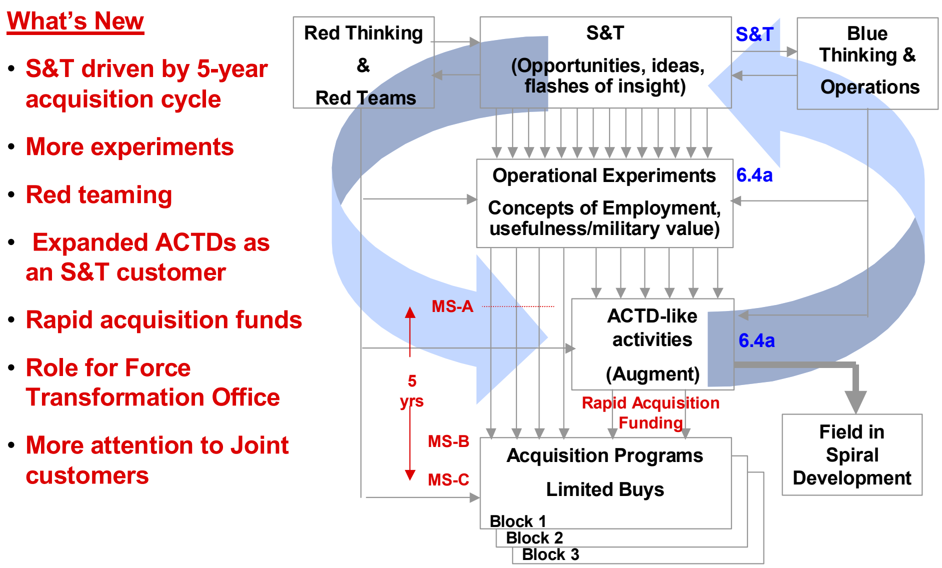
Figure 4-2 depicts the dynamic and iterative process recommended by the task force. The new features enumerated on the left are discussed in more detail in the following sections.

SHORTEN THE DEVELOPMENT TIME TO NO MORE THAN FIVE YEARS

The USD (AT&L) has issued a directive calling for the engineering and manufacturing development (EMD) process to be reduced to an average of seven years, from the 10-year-or-more norms of the past several decades***. The task force recommends going further reducing this time to a maximum of five years, and even fewer for systems smaller than Major Defense Acquisition Programs***. This mandate would make the S&T base a critical antecedent for the development and acquisition of

military systems. Only when the relevant S&T base has become mature can the system pass through EMD in no more than five years, as both commercial and military experience has demonstrated.

Figure 4-2. The Expanded Spiral Development Process



In addition to establishing a mature S&T base, several other factors are essential for rapid execution of a system development program:

1. The necessary competence and capability to develop and manufacture the system must be available. The capability will draw heavily upon the S&T base, and on the manufacturing infrastructure and sub-system suppliers.
2. The system acquisition authority must be dedicated to acquiring the system. If interest in the system acquisition is weak or dilatory, the acquisition community will not be able to generate the resources and focus to develop the system.
3. The total funding to take the system through EMD must be identified and available. The DoD budget always extends beyond five years, so the EMD budget will be known, fully identified, and programmed at the outset. Budget or time over-runs should be presumptive causes for system development termination.

4. The acquisition authority and the system user community must be willing to accept the production and deployment of an initial version of a system, even though more advanced versions can be imagined, with the understanding that through spiral development, subsequent design cycles will produce more capable versions of the system.

Major costs are incurred when the EMD process lasts longer than it must, including (1) the cost of sustaining the infrastructure necessary for carrying out the EMD, and (2) the cost of money invested but not yielding a useful product for an extended period of time. Consequently, major savings can be achieved over time just from shortening the EMD process.

Place More Emphasis on Experimentation

Operational experimentation is an essential ingredient of transformation and the mechanism to explore coherent and connected changes to doctrine, organization, technology, training, and the other human dimensions needed to produce new warfighting capabilities and concepts. Experiments differ from exercises and demonstrations. Experiments, searching for breakthrough change, are more speculative endeavors than ACTDs. Experiments fail only when nothing of significance is learned. Concepts can "fail." Indeed a major purpose of experiments is to challenge proposed concepts for vulnerabilities in order to learn how to make them more robust or discard them for more promising alternatives.

Experiments need not be huge affairs. Most experimentation can be relatively small in scale, including tens or hundreds of participants rather than thousands. Collaborative interaction between technologists and operators is one priority. Through campaigns of aggressive experimentation, many ideas can be pursued.

Successful experimentation requires an environment that fosters innovation, competition of ideas, and risk taking. It also requires including some operational units at the heart of experiments; without them, the doctrine, organization, and other dimensions of new military capabilities will not evolve along with technology and materiel. Examples of units already used in such a capacity include the 9th ID/ADEA at Ft. Lewis, the F-117 squadron used in the 1980s, and elements of the Army's 4th ID used in the Army's recent Digitization efforts. In addition, dedicated and high-quality red teams and opposing forces are needed to

make experimentation successful—a topic discussed further in the next section.

DoD must develop and innovatively use simulations and synthetic environments that allow real people to experiment with virtual systems. The usefulness of virtual systems should not be dismissed because of artificialities; all experimental venues short of war are artificial in one way or another—even field experiments with real troops and equipment bring their own artificialities.

Recommendation: The Chairman, Joint Chiefs of Staff (CJCS), should form experimental units in each Service and Joint Forces Command (JFCOM).

- Units should have dedicated command staffs.
- Forces should be assigned to these units as appropriate for each experimental series.
- The CJCS should form corresponding, dedicated operational red teams.
- Senior officials should be assigned responsibility for fostering operational innovation and full use of experimentation.
  - The task force suggests Vice Chiefs and J-8 with accountable responsibility.

The USD (AT&L) should provide funds for joint & multi-Service experimentation and fund and support increased use of ACTDs.

INCREASE THE USE OF RED TEAMING

A necessary component of spiral development is extensive use of red teams, particularly those designed to serve as surrogate adversaries. Red teams are needed to challenge ideas and concepts throughout the entire technology development process.

Too often, the red team is not considered at all, is treated as an afterthought, involves adversary play that is merely scripted (otherwise the uncertainty involved might spoil the demonstration), or consists of pitting presumed future capabilities against today's adversary. None of these approaches will lead to the robust capabilities and concepts needed against real-world adaptive and resourceful adversaries. Thus, an essential

ingredient of spiral development is the presence of red teams serving as surrogate adversaries.

Effective red teaming will be a challenge. A major difficulty is to capture the cultural and social perspectives of potential adversaries and not merely a mirror image of U.S. attitudes. While the red team should have a considerable degree of independence from the concept and technology developer and other program advocates, the red team must also interact with the concept and technology developers to avoid becoming mere sideline critics.

Recommendation: Increase the use of red teaming in experimentation and other phases of spiral development. Red teaming also needs an advocate in the system to ensure quality, relevance, and the right mix of independence from and interaction with the concept and program advocates.

EXPAND ACTD EFFORTS

One of the goals elaborated by the USD (AT&L) is to encourage the exploitation of mature technology. One way to encourage such use is to increase the demand. ACTDs are customers of mature technology and thus increasing the ACTD activity will provide a stronger customer pull for such technology. The task force appreciates that ACTDs are not the appropriate venue for all development activities; but while it did not attempt to determine the ultimate limits of ACTD-type activity, the task force is confident the current activity can be expanded by at least a factor of two without fear of hitting any such limits.

The enhancement of ACTD activities should not be limited to merely increasing the number of ACTD projects. Some of the additional funds in an expanded ACTD activity should be allocated to preparing the results of individual projects for transition to acquisition and other downstream activities. This transition can be facilitated by securing greater involvement of the acquisition and test communities in ACTD projects.

Recommendation: Increase funding for ACTDs by a factor of two.

Establish and Increase "Bridge Funding" for Service and for Joint Activities

Sometimes demonstrations and experiments seem to become stuck in a circular process rather than the desired spiral development process. The Services experiment and learn, but lack mechanisms to promote and transfer what it learns. As a result the Services tend to conduct similar experiments or demonstrations to learn the same thing again and again. The Army is successfully using its Rapid Acquisition Program funds to help transition promising results from experiments and demonstrations to fielded capabilities.

Recommendation: Expand the use of rapid acquisition funds, particularly applied to joint needs where the processes and organizations are least mature and least effective.

Establish a Strong Role for the New Office of Force Transformation in Fostering Transition as Well as New Thinking

Last fall, Secretary of Defense Rumsfeld established the Office of Force Transformation, directed by VADM Art Cebrowski, USN (ret.). The task force believes that the creation of this office offers an opportunity to implement several key elements of the strategy proposed in this report.

The task force suggests that rather than focusing only on farther out, so-called "out of the box" ideas, the new office be granted the authority and resources—both staff and funding—to push transformation on a much broader front. Specifically, the task force recommends that the new office's responsibilities include the following:

Recommendation: Assign the Office of Force Transformation responsibility for sponsoring experiments.

- Identify and support worthy experimentation candidates.
- Have funds and lead a non-bureaucratic process to couple S&T products (prototypes and surrogates) to warfighters.
- Focus on joint and multi-Service needs, working closely with JFCOM. Generally, JFCOM has mostly emphasized large annual events (although it is increasing attention to the smaller, and potentially higher-risk limited objective experiments).

Recommendation: Assign the Director of the Force Transformation Office responsibility for ACTD.

Experiments and ACTDs differ, but share important similarities as well. The two are similar in that they involve a close relationship between technologists and operators. A key difference, however, is that ACTDs are further downstream—closer to fielding—and indeed most often have a requirement for field-ready results. Experiments tend to be more speculative. ACTDs generally work with "prototypes," experiments with "surrogates."

The similarities and differences can be exploited in the service of transformation by bringing the two activities closer together organizationally and functionally. The two can feed each other. The appropriate next step following an experiment may often be to conduct one or more ACTDs. Furthermore, the team assembled to conduct an ACTD is often trained and well prepared to explore concepts that are more speculative, via surrogates in experiments.

Tying the ACTD programs with the Office of Force Transformation also offers the opportunity to identify and oversee ACTDs within a larger transformation context, thus more closely coupling the "thrust" provided by multiple ACTDs with the "vector" provided by a transformation vision.

Recommendation: Provide the Director of Force Transformation responsibility for managing a "Bridge Fund" account.

As already discussed, a major deficiency of the current technology development process, particularly for joint needs, is the lack of mechanisms to pull forward promising results from experiments and ACTDs. The Office of Force Transformation would be an appropriate place to provide the funds for this function—creating a program similar to the Army's Rapid Acquisition Program.

Recommendation: The Secretary of Defense should empower the new Office of Force Transformation with the authority, staff, and funding to sponsor the prototypes (real and virtual), surrogates, ACTDs, and modeling and simulation for transformation experimentation, demonstration, and testing, especially multi-Service and joint.

- Funding should grow to $200 million per year for experiments; to $250 million per year for ACTDs.

Recommendation: Fund the Office of Force Transformation to sponsor the new Joint Warfighting Rapid Acquisition Program to speed fielding high-pay-off products (not limited to materiel) from joint experimentation and ACTDs.

- Funding should grow to $150 million per year.

STRENGTHEN S&T SUPPORT TO JOINT AND NATIONAL-LEVEL CUSTOMERS

The S&T community needs to pay more attention to the needs of future joint and national-level customers in addition to Service-specific needs.

In critical areas of joint concern, specifically joint command and control; joint connectivity and interoperability;, and intelligence, surveillance, and reconnaissance (including the associated sensor management, fusion, and exploitation tools) lack a 6.4 development organization—that is, an S&T customer. The absence of an organization to serve as the S&T customer implies a lack of support to warfighters in their number one area of concern, namely joint command and control; weak paths to the user for S&T in these critical areas; weak joint pull on S&T; and no integrated view of systems or solutions. This has long been recognized as a problem but progress has been discouraging.

The major national-level concern that requires S&T support is the biological warfare threat (covered in another section of this report). However, the task force focused on recommendations for joint command and control, since it is so fundamental to transforming U.S. military capabilities.

Recommendation: Assign JFCOM the responsibility to:

- Develop and test joint command-and-control system prototypes using spiral development.
- Establish a standing experimental Joint Task Force Headquarters at JFCOM.
- Work with regional combatant commanders to transition the joint command and control system to them, tailoring the capabilities to each.

This formidable task will severely challenge the current capabilities and organization of JFCOM. Relieving CINCJFCOM of his responsibilities as the Supreme Allied Commander, Atlantic, would free

him to focus on transformation. JFCOM will also need access to additional resources and partners.

Recommendation: Provide JFCOM the technical, system engineering, and acquisition capabilities and partners needed to accomplish these responsibilities for joint command and control:

- Partner with the Defense Advanced Research Projects Agency to produce a flow of new technology.
- Create a system engineering capability at JFCOM to provide configuration control and other system engineering functions.
- Create a Joint Program Office to acquire and deploy a joint command and control capability.
- Partner with a Federally Funded Research and Development Center for technical support.

The task force also recommends providing Category 6.4 funds to the regional combatant commanders to address near-term joint problems unique to their area of responsibility and to support JFCOM's experimental and prototype development efforts on behalf of future combatant commanders.

EXPLOIT COMMERCIAL AND OTHER NON-DOD SOURCES OF TECHNOLOGY

The case for greater exploitation of commercial technology, processes, and products by DoD has been made many times, including by previous DSB task forces. Recommendations of these studies have since been adopted, some into federal acquisition policies. Nevertheless, much more still needs to be done, as the Department continues to deny itself access to many industries.

The trend to commercial leadership in information technology, biology, microelectronics and other important technology areas has, if anything, accelerated. The emphasis on reducing DoD's own time-to-market intensifies the need for broader and deeper DoD access into the commercial technology base. Because this technology base is increasingly global and available to potential adversaries, exploitation of this base by

DoD becomes critically important in order to understand how adversaries might threaten the United States with these technologies.

The aerospace industry, which has historically provided advancements and new technologies to DoD, has consolidated significantly. Its primary focus is now the application of military-specific technology, and to some extent commercial technology, to military systems. As the supply base for this technology shrinks, it becomes increasingly important to improve the ability and incentives for non-aerospace commercial companies to support DoD.

The Department needs to find ways to more aggressively leverage commercial technology in order to exploit the very best technologies at affordable prices and to understand potential threats. A complementary multi-pronged approach is required. It must encompass the following:

- Reducing the barriers that inhibit commercial firms from working with DoD contractors and with DoD directly.
- Motivating DoD to turn to commercial products, practices, and processes as the norm rather than the exception.
- Fostering relationships with critical technology sectors so they are motivated to apply their knowledge and personnel to address grave national security threats (the potential for success in this area may have increased since September 11, 2001) and to consider DoD needs in new product development.

Each of these strategies is discussed in greater detail in the next sections.

REMOVE BARRIERS AND DISINCENTIVES FOR COMMERCIAL FIRMS

Many commercial companies and laboratories avoid doing business with the federal government for three primary reasons. First, the requirement that commercial firms submit cost data that is not normally generated by their accounting systems and is often considered proprietary. Second, the requirement for access to and, in some cases, ownership in intellectual property. Finally, commercial businesses are concerned about potential liability (legal as well as corporate reputation) based on understanding and complying with complex DoD regulations and policies.

In addition, for many of these companies, an opportunity to do business with DoD is neither significant nor attractive. Since commercial

companies are accustomed to selling to customers who buy their products, they are rarely attracted to DoD, which essentially acquires materiel.

Although many commercial technologies can provide significant potential benefit to the military sector, most companies are reluctant to accept contracts covered by the Defense Federal Acquisition Regulations. This is especially true when procuring R&D from commercial laboratories.

Previous studies have found that the issue of intellectual property rights is often a significant deterrent to commercial firms doing business with DoD (see *Performing Collaborative Research with Nontraditional Military Suppliers*, RAND Corporation). Intellectual property is the life-blood of high=technology industries and provides significant competitive advantage. Success in these commercial markets depends largely on superior product performance and a strong intellectual property rights position. Intellectual property establishes the company's sole-source position within a market; this position in turn leads to higher profit margins.

The current federal intellectual property rights policies are primarily based upon the Bayh-Dole Act of 1980 (by Presidential Memoranda; see 35 U.S.C. 202-204). Initially, the act applied only to small businesses and nonprofit organizations, but it was extended to all contractors in 1983. The act provides that title to any invention or discovery made or first actually reduced to practice under any contract, grant, or cooperative agreement between any federal agency and any contractor may be retained by the contractor subject to the right of the government to a non-exclusive, nontransferable, irrevocable, worldwide, paid-up license to practice or have practiced for or on behalf of the government.

The act was designed to enable the government to secure parts and assemblies for weapon systems from multiple sources. Through specific clauses in the Defense Federal Acquisition Regulation, the government reduces the act to practice by specifying ownership to technical data rights (covering trade secrets and process information). Though the government rarely asserts its "march in" rights, the threat of such action is significant enough that most commercial companies do not choose to do business with DoD for fear of sharing valuable intellectual property with their competitors.

Recommendation: DoD should develop and implement acquisition policies and processes that remove barriers and create incentives for commercial corporations to support DoD needs.

DoD should develop new policies for such issues as ownership of intellectual property, liability indemnification, accounting, audit, allowable costs, disclosure requirements, and hurdles to foreign ownership and control. Use of commercial parts may not provide a sufficient motivation for prime contractors because there is little incentive to change or save costs in existing programs and proprietary rights.

PROVIDE STRONGER MOTIVATION TO THE DOD REQUIREMENTS AND ACQUISITION COMMUNITIES TO USE COMMERCIAL TECHNOLOGY AND PRODUCTS

Through various policy initiatives, the USD (AT&L) has made significant progress over the past several years in promoting greater use of commercial technology in weapons acquisition programs. Increased focus on procuring commercial items for DoD systems is reflected in DoD Directive 5000.1, which states that using commercial items in DoD systems is the preferred approach for meeting operational requirements.

Though the leadership within USD (AT&L) has established clear directives for the use of commercial items, the acquisition community has not been as quick to embrace the new acquisition policies. The DSB task force report, *Impact of DoD Policies/Practices on the Health/ Competitiveness of U.S. Defense Industry* (April 2000), presented the following findings:

> *The DoD acquisition process continues to be unreasonably risk-averse, which inhibits innovation and access to creative, high technology solutions. Senior DoD leadership is focusing in the right direction, but the reality at the workforce level (in government and to a degree in industry) is different.*
>
> - *The acquisition workforce works under constant scrutiny and criticism, and there is little perceived support for calculated risks.*
> - *The oversight community, at the operating level, continues to operate in a "gotcha!" manner, with little understanding of or sympathy for the changing dynamics of the market or industry.*
> - *This environment inhibits creativity in the DoD industrial base and helps drive suppliers out of the DoD market.*

A number of specific obstacles hinder accession of commercial items for DoD use. For example, the requirements process rarely considers cost

and design tradeoffs or adequately evaluates existing commercial technologies. The acquisition workforce lacks experience with and knowledge of commercial markets. Decisions made on commercial item determination are inconsistent; market research is weak; and there is confusion concerning how to price commercial items. Moreover, DoD procedures regarding commercial items are inconsistently applied (applicability of Federal Acquisition Regulation Part 12 determinations). Finally, risks and costs are associated with testing, qualifying, and inserting commercial components.

Using commercial technology, DoD will have better access to replacement and repair parts and to software—including state-of-the-art technology—since new versions are constantly being introduced into the commercial marketplace. By taking the necessary steps to use drop-in replacement components or commercial off-the-shelf products and using software, DoD will greatly alleviate its problems with providing custom replacement components and software that falls far short of the state of the art. Since some of these components will come from foreign manufacturing facilities or even foreign corporations, systems and processes will need to be developed for wartime needs; given the current foreign content and ownership status, this need is present today.

Recommendation: DoD must change its acquisition system and mandate that using commercial practices, components, materials, software, tools, and processes will be the norm.

Justification for non-commercial DoD-specific acquisition of technology should be considered appropriate, and in fact required, when DoD-specific requirements (such as stealth) are needed. Program managers—with support from prime contractors—should be responsible for ensuring that the commercial content mandate is met. These policies should also flow down to the subcontractors. In addition, DoD should make wider use of Section 845 procurements.[33]

[33] "Other transactions" are instruments other than a contract, grant, or cooperative agreement for carrying out research projects. The authority's primary purpose is to help broaden DoD's technology and industrial base by allowing development and use of instruments that reduce barriers to participation in defense research by commercial firms that traditionally not done business with the government. Section 845 of the National Defense Authorization Act for Fiscal Year 1994 augmented the "other transactions" authority by authorizing DARPA to use "other transactions" for prototype projects directly relevant to weapon systems proposed to be acquired or developed by DoD. This extended authority was later provided to the military departments and other designated officials.

Motivate Critical Technology Sectors to Help Address National Security Challenges

In the commercial sector, many large corporations—U.S. and foreign-owned—have evolved into multinational organizations that are expanding their business, manufacturing, and technology globally. With the dispersion of technology and the speed of modern communications, U.S. adversaries—large and small—will have rapid access to commercial technology that can considerably enhance their military capability.

If the United States does not develop the means to track and use this technology, our country will be put at a significant disadvantage. For certain key technologies—such as microelectronics, software, biotechnology, pharmaceuticals, robotics, and materials—DoD is now a minor player in development and use.

In particular, DoD needs to build a strong partnership with the bioscience and pharmaceutical industries for both R&D and supply. This requirement is so important that Secretary Rumsfeld's understanding of the pharmaceutical industry should be leveraged into meetings with the industry leaders so that they can establish an NSTAC-like relationship.

Next Steps for the USD (AT&L) and Secretary of Defense

Recommendation: The USD (AT&L) should

- Mandate the use of commercial practices, tools, techniques, components, software, and materials in DoD systems by establishing commercial technology as the norm and requiring justification for DoD-specific technology.
  - Implement at the program-manager level through the prime contractor.
- Develop and implement acquisition processes that remove barriers (identified in past studies) and create incentives for commercial corporations to support DoD.

The Secretary of Defense should

- Personally engage with bioscience and pharmaceutical industries to build relationships with DoD.

  - Take advantage of the Secretary's understanding of the industry.
  - Create effective partnerships between DoD and these industries and research institutes.
  - Consider a NSTAC-like relationship.
- Forge close relationship with the Secretary of Health and Human Services (National Institute of Health, Center for Disease Control).

MAKE THE DOD LABORATORIES MORE EFFICIENT AND MORE PRODUCTIVE

IDENTIFICATION OF DOD LABORATORIES

Generally, "DoD laboratories," refers to a collection of organizations that manage and consume S&T funds (6.1, 6.2, and 6.3 funds). These laboratories include 40 to 50 organizations at some 78 to 84 locations; the exact number depends on the specific definition. They include organizations that vary a great deal in size, mission, and the degree to which S&T funding contributes to their total funding. The range of organizations includes in-house research establishments—such as the Army's Walter Reed Medical Center and Research, Development and Engineering Centers that use a smaller fraction of S&T funds—and certain test organizations that manage some S&T funds incidental to performing specific tests for S&T projects.

FUNDING OF DOD LABORATORIES

Much of the funding that flows through or is expended in DoD laboratories is not S&T funding. The majority of funding for DoD laboratories comes from non-S&T, research, development, test and evaluation (RDT&E) funds (6.4 and 6.5), and operations and maintenance funds. However, the majority of S&T funds, about $5 billion of the $9 billion, flow through DoD laboratories according to the S&T financial reporting system. This figure includes the portion of DARPA S&T funding that is formally transferred to DoD laboratories for execution; it does not include funds that DARPA places directly but asks a DoD

laboratory to help manage. Of the $5 billon in S&T funding flowing into DoD laboratories, about half ($2.5 billion) is consumed in performance of in-house operations and research.

Thus, the DoD S&T laboratories manage more than half of all DoD S&T funds and internally consume one-quarter of those funds. The quality of the laboratories is therefore a major influence on the quality of the S&T performed across DoD.

Non-research activities performed by these organizations include engineering development, test support, in-service support and engineering, and support to the acquisition process. In many cases, the laboratory predominantly focuses on support to formal acquisition programs, and the S&T activity is relatively small, though essential to the overall mission.

Personnel Issues at DoD Laboratories

The total staff within DoD laboratories that are coded as "scientists and engineers" (S&E) number some 25,000 individuals; the total DoD-wide scientific and engineering population is about 114,000 individuals. These other scientists and engineers are primarily engaged in support of acquisition, logistics, and operations. Of the 25,000 S&E personnel in DoD laboratories, the majority work only part-time on S&T activities because their time is heavily committed to acquisition programs.

As a result of extensive intermingling of S&T and non-S&T activities at the organizational level and extensive crossing of the S&T lines by individuals, efforts to improve recruitment within the more research-oriented laboratories run headlong into concerns of fairness and discrimination.

Clearly, DoD laboratories form an essential and vital link in the DoD S&T program. They require a quality workforce not only to perform in-house work but also to manage and direct those S&T activities that are performed on contract. That quality workforce is also essential to support DoD's acquisition programs.

Numerous prior studies by the DSB and others have raised serious concerns about the current quality and qualifications of the workforce; more importantly, there is concern about the Department's ability to recruit and retain quality personnel in the future. Some laboratories have made heavy use of non-traditional sources of personnel, such as interns, those hired under the Intergovernmental Personnel Act, and visiting scientists. These measures have helped to a limited extent.

The government's reluctance to establish special arrangements for S&E personnel is widespread and deeply ingrained. Many reforms have been promulgated, but they have not been fully implemented. At the core of such reluctance is the difficulty of deciding where to draw the line. Some S&E personnel work alongside non-S&E personnel, while some S&E personnel are not performing functions that require S&E qualifications. Thus, it is very difficult to fairly administer many reforms that otherwise appear useful.

Nonetheless, after due consideration of the value and the difficulties, prior reviews of the needs of DoD laboratories have uniformly called for serious reform; the only differences are in the details and in the degree of reform deemed achievable. The task force believes the Department should conduct an in-depth review of each of the DoD laboratories to review its activities, understand its functions, and understand its workforce. On the basis of this information, the Department can reshape the laboratory structure. Personnel, activities, and facilities involved in acquisition can be transferred into acquisition organizations. Laboratories with a strong S&T or technology orientation, with significant in-house research, should be moved to university management to relieve them from the restrictions of the civil service personnel system. Other laboratories might be considered for privatization, consolidation, or closure.

Whether or not the Department undertakes such a review, the task force recommends the Department implement the recommendations of the most recent Defense Science Board study of the laboratories, *Efficient Utilization of Defense Laboratories*. This study provides an in-depth review of these past studies and a thoughtful set of detailed recommendations for reform.

Recommendation: The USD (AT&L), with direction of the Secretary of Defense, should direct DDR&E to do the following

- Review each laboratory in detail and proceed with each individually.
  - Administratively transfer personnel not involved in S&T to acquisition organizations.
  - Move personnel doing significant in-house research or technology development to university management.
  - Privatize, consolidate, or close other laboratories.
- Complete the review and begin taking action within nine months, with an end goal of 2005.

- In any case, especially for those laboratories likely to remain status quo, implement recommendations of most recent DSB study (*Efficient Utilization of Defense Laboratories*, October 2000).
  - Focus on personnel and quality improvements.

ALLOCATION AND LEVEL OF S&T FUNDING

ALLOCATION OF FUNDING

In fiscal year 2001, DoD allocated about 22% ($41 billion) of its total budget to research, development, testing, and evaluation of new technologies and systems. Science and technology funding of approximately $9 billion represents about 22% of the RDT&E budget and 2.7% of the total DoD budget, as Figures 4-3 and 4-4 illustrate.

The S&T funding includes categories 6.1 (Basic Research), 6.2 (Applied Research), and 6.3 (Advanced Technology Development). The remainder of the RDT&E budget allocates about $31.85 billion for System Development and Demonstration (6.4–6.7 funding categories), as well as a small amount (about $150 million) for Rapid Acquisition Funds.

Figure 4-3. RDT&E Funds as Percentage of FY01 DoD Budget

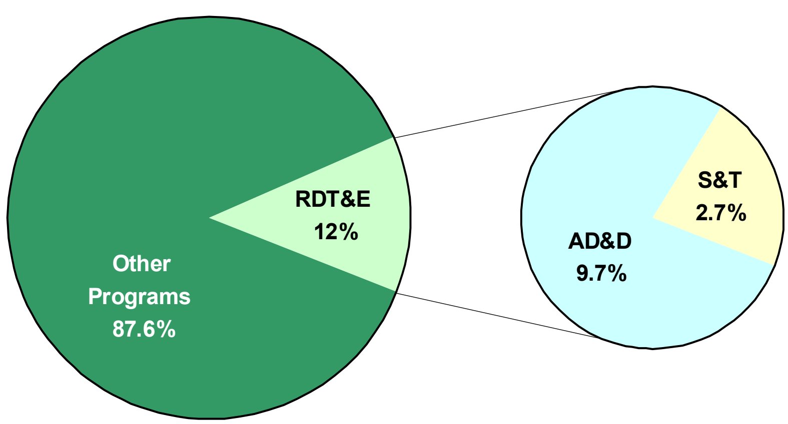
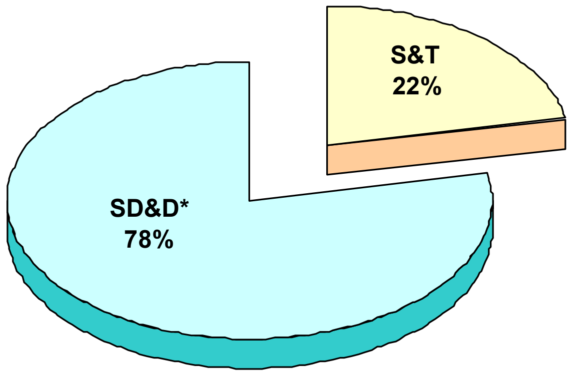


Figure 4-4. S&T Portion of DoD RDT&E Funding



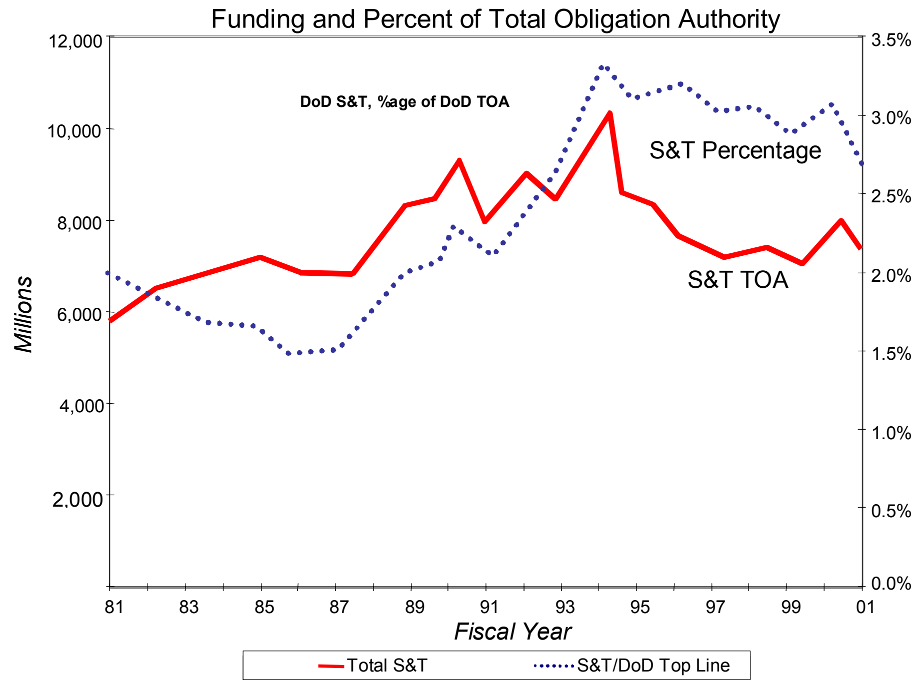
*Includes $150 million for Rapid Acquisition Funds

As Figure 4-5 shows, the funding allocated for S&T has decreased both in absolute terms and as a percentage of the DoD budget over the past decade.

The DoD S&T programs are further classified into six categories:

- ***Sustaining S&T***. Ongoing programs in technologies of historical interest to the military, such as material science, information technology, electronics, and sensors.
- ***Focused S&T Programs***. Research areas that have or should have a central focus and coordination across DoD, such as biological warfare defense and S&T on intelligence, surveillance, and reconnaissance.
- ***New S&T Projects***. Technologies not previously funded that have significant military benefits.
- ***Long-Term Research***. Technologies that have the potential of being disruptive in nature but are many years away from any practical application. Examples include nanotechnology and quantum computing, discussed in the previous chapter.
- ***S&T Experiments.***
- ***ACTDs.***

Figure 4-5. ***DoD Science and Technology Funding***



ACHIEVE AND SUSTAIN THE 3 PERCENT S&T FUNDING LEVEL

There is no magic formula to determine the optimum level of S&T funding. Several recent studies have addressed issue. In its report, *Defense S&T for the 21st Century* (1998), the DSB force recommended an S&T funding level equivalent to 3 percent of the total DoD budget. This figure is in keeping with the research and development budgets of various commercial industries, in terms of the percentage of sales spent on research and development.

The task force agrees that 3 percent is a reasonable funding level. DoD leadership has concurred in recent testimony to Congress. Furthermore, support appears to exist within DoD and on Capitol Hill for achieving this level based upon historical DoD S&T budgets. ***Therefore the task force recommends that the Secretary of Defense achieve and sustain the 3 percent S&T funding level (of top-line DoD budget), recommended by the prior DSB study.***

REALLOCATION OF FUNDING AND REPRIORITIZATION OF EFFORTS

In addition to sustaining a 3-percent level of DoD S&T funding, ***the task force recommends reallocating funds to promote transformation within the DoD S&T community***. This transformation would emphasize four elements:

- The integrated process of operational experimentation and spiral development.
- More rapid and effective transition of technology to the warfighter (through strong customer influence).
- Exploitation of commercial technology.
- Targeted funding of specific S&T initiatives (those areas discussed in the previous chapters of this report):
  - Defending against biological warfare defense.
  - Finding difficult targets (intelligence, surveillance, and reconnaissance S&T; micro-sensor networks).
  - Making timely, accurate decisions (decision tools, multi-player gaming).
  - Enabling high-risk operations (human performance, unmanned systems).

To speed up the transition of technology and motivate experimentation, the task force recommends that ACTD funds be moved from under S&T (6.3) funds and placed under 6.4A. The task force also recommends that the current funding for ACTDs ($500 million) be doubled to $1 billion. Other recommendations include allocating $200 million for 6.4A experiments and an additional $200 million for rapid acquisition funds (to $350 million).

New S&T initiatives, totaling $2 billion, would be funded within the $9 billion S&T budget by implementing the following strategies:

- Move and fund ACTDs under 6.4A and return current funding to 6.3 (~$500 million/year).
- Increase S&T from 2.7% to 3.0% (~$250 million /year).
- Reprioritize investments and reallocate the S&T portfolio over the next two to three years (about 15 percent of the S&T budget or ~$1,250 million /year; could be higher).

The following criteria will be useful for selecting which current efforts to terminate through reprioritization. Termination should be considered when

- DoD technology is far behind efforts in the commercial sector.
- DoD can rely on commercial technology and broadly understands it.
- An effort is sub-critical in size.
- Output is likely to have low or limited application.
- Efforts are unproductively redundant in multiple places.
- Successful conduct will not make a difference.
- DoD otherwise anticipates low value in payoff of project.

In addition to reprioritizing the current S&T investment, DoD can also take advantage of the natural annual shifts of the S&T investment portfolio resulting from technology changes. Annual turnover of S&T programs could free upwards of 20 percent of the S&T funds associated with "sustaining S&T."

Recommendation: The USD (AT&L) should

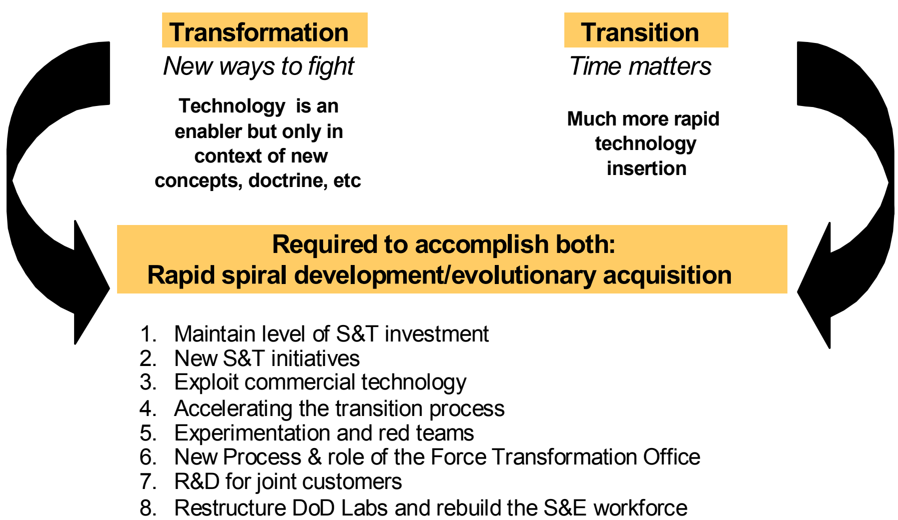
- Direct reprioritization of S&T to fully fund the S&T initiatives outlined, within the S&T budget.
- Start now and complete reprioritization within nine months.
- Provide $500 million of 6.4A funds to move current ACTDs from 6.3 and use current 6.3 funds as part of funding of new initiatives.
- Re-institute the "Format-I" to provide muscle for the DDR&E to effectively control focused ongoing S&T programs.
- Establish single focal point for BWD S&T.

The Secretary of Defense should achieve and sustain investment in S&T of 3 percent (of top-line DoD budget).

SUMMARY OF RECOMMENDATIONS RELATED TO THE S&T ENTERPRISE

Figure 4-6 summarizes the dominant themes of this chapter. Technology is one enabler of new military capabilities and is typically most effective only in the context of new concepts of operations and doctrine. To accomplish both transition of technology to the field and transformation of military capabilities, the Department must change its S&T enterprise through operational experimentation, rapid spiral development, and evolutionary acquisition. Only then will the Department be able to fully realize the benefits of the S&T investments described in this report.

Figure 4-6. Two Challenges That Will Change the Nature of the S&T Enterprise and U.S. Military Capability



The recommendations in this chapter focus on transforming the Department's S&T enterprise. They fall in eight areas:

1. ***Maintain the level of S&T investment*** at 3 percent of the overall DoD budget as currently planned by the Department. Provide additional funds for new S&T priorities by reprioritizing current programs and shifting funds for ACTDs to the 6.4A account.

2. ***Invest in new S&T initiatives in support of four transformational challenges***: defending against biological warfare; finding difficult targets; making timely, accurate decisions; and enabling high-risk operations. Expand and provide more focused management for ongoing related S&T programs.

3. ***Exploit commercial technology*** through expanded use of commercial products and processes; elimination of barriers; and efforts to forge relationships with commercial industry.

4. ***Embed R&D activities in a broadly applied spiral development process*** with a five-year maximum acquisition time and an expanded ACTD program

5. ***Foster discovery and learning through operational experimentation and extensive use of red teams***, as an integral element of a new S&T enterprise, through assigned experimental units and sustained senior attention.

6. ***Establish a new technology transition process*** by assigning responsibilities and resources to the Director of Force Transformation for sponsorship of joint operational experiments, stewardship of ACTDs, and a strong role in transitioning results from these activities.

7. ***Accelerate the transition process for joint R&D*** by establishing points of responsibility in joint C4ISR and biological warfare defense.

8. ***Restructure the DoD laboratories and rebuild the scientific and engineering workforce*** based on a major review of the function and workforce in each laboratory.

ANNEX A.

TERMS OF REFERENCE

ACQUISITION AND TECHNOLOGY

THE UNDER SECRETARY OF DEFENSE

3010 DEFENSE PENTAGON
WASHINGTON, DC 20301-3010

14 DEC 2000

MEMORANDUM FOR CHAIRMAN, DEFENSE SCIENCE BOARD

SUBJECT: Terms of Reference Defense Science Board Summer Study on Defense Science & Technology

You are requested to form a Defense Science Board (DSB) Summer Study to address the issues involved in assuring that the U.S. continues to gain access to and develop technology from which to gain military advantage.

Technology has been and must in the future continue to be a key enabler of military advantage, both in conflict and in situations in which conflict is close at hand. The DoD science and technology program over the years has discovered, invented, harnessed, and/or demonstrated such enabling technologies. As industry has globalized, as science endeavors in other nations become more competitive, and as affordable technology increasingly issues from commercial sources, the DoD science and technology program needs to continually adapt to meet challenges and exploit opportunities.

You are to consider future technologies that should be developed and exploited for military application. Of particular concern should be potential technologies that provide the U.S. military an asymmetric advantage – in conflict, but also in cost-effectively maintaining a ready and motivated force at home and in deployment situations where conflict is not engaged, but appears to be imminent.

You are to consider the appropriate mix of in-house, contractor, university and commercial providers of basic and applied research and of advanced development. Your Task Force should recommend both the level of investment and the characteristics of S&T investment that the DoD should make. Recommend how the DoD can leverage technology that is under development and produced globally in commercial industry as well as that which is being discovered and demonstrated in the science and technology programs funded by both other U.S. agencies and other nations. You should consider the situation of and the contribution of the DoD laboratories in this changing world. The Task Force should also consider how to maintain excellence in in-house science and technology endeavors.

The study will be co-sponsored by the Under Secretary of Defense (Acquisition, Technology and Logistics) and the Deputy Under Secretary of Defense (Science and Technology). Dr. Anita Jones and Mr. Larry Lynn will serve as the co-chairs of the Task

Force. Dr. Lew Sloter will serve as the Executive Secretary, and LtCol Tony Yang will serve as the DSB Secretariat Representative.

The Task Force will be operated in accordance with the provision of P.L. 92-463, the "Federal Advisory Committee Act", and DoD Directive 5105.4, the "DoD Federal Advisory Committee Management Program". It is not anticipated that this Task Force will need to go into any "particular matters" within in the meaning of Section 208 of Title 18, U.S. Code, nor will it cause any member to be placed in the position of acting as a procurement official.

J. S. Gansler

ANNEX B.

TASK FORCE MEMBERSHIP

Co-Chairs

Dr. Anita Jones	University of Virginia
Mr. Larry Lynn	Private Consultant

Executive Secretary

Dr. Lewis Sloter	ODUSD(S&T)/Weapons Systems

Military Applications Panel

Gen (R) Mike Carns (Co-Chair), USAF	Private Consultant
Mr. Frank Kendall (Co-Chair)	Private Consultant
Mr. Ed Brady	Strategic Perspectives, Inc.
Gen (R) Wesley Clark, USA	Stephens Group
Gen (R) Wayne Downing, USA	Downing & Associates, Inc.
Dr. Michael Frankel	SRI International
Gen (R) Dave Maddox, USA	Private Consultant
Mr. Walt Morrow	MIT Lincoln Laboratory
RADM (R) Marc Pelaez, USN	Newport News Shipbuilding
Dr. Robert Rankine	Private Consultant
MG (R) Robert Scales, USA	Walden e-Learning Inc.
Gen (R) Larry Welch, USAF	Institute for Defense Analyses

Investment Strategy Panel

Dr. Ted Gold (Co-Chair)	Institute for Defense Analyses
Dr. Lydia Thomas (Co-Chair)	Mitretek Systems
Mr. Denis Bovin	Bear, Stearns & Co. Inc.
Dr. Jacques Gansler	University of Maryland
Dr. Bill Graham	National Security Research
Dr. Barry Horowitz	Concept Five Technologies
Dr. Ron Kerber	Private Consultant
Mr. George Singley	Hicks and Associates, Inc.
MajGen (R) Jasper Welch, USAF	Jasper Welch Associates

Technology Panel

Dr. Regina Dugan (Co-Chair)	Dugan Ventures
Dr. Peter Lee (Co-Chair)	Carnegie Mellon University
Dr. Ruth David	ANSER
Dr. Larry Dubois	SRI International
Dr. Ken Gabriel	Carnegie Mellon University
Dr. James Heath	UCLA
Mr. William Koos	MILCOM
Dr. Gregory Kovacs, MD	Stanford University
Dr. Patrick Lincoln	SRI International
Dr. Stephen Rockwood	SAIC
Dr. Michael Roukes	California Institute of Technology
Pat Scannon, MD	XOMA, Ltd.
Judy Swain, MD	Stanford University
Mr. Dick Urban	Charles Stark Draper Laboratory
Dr. Haydn Wadley	University of Virginia
Mr. Owen Wormser	C3i

DSB Representative

LtCol Roger Basl, USAF	DSB

Government Advisors

CAPT John Costello, USN	Joint Staff J-8
Dr. Paris Genalis	Naval Warfare
Ms. Vivian George	Night Vision Lab
Dr. Genevieve Haddad	AFOSR/NL
CAPT Shaun Jones, USN, MD	
Col Mike Perrin, USMC	Joint Staff J-8
Ms. Mary Scott	National Ground Intelligence Center

Staff

Ms. Barbara Bicksler	Strategic Analysis, Inc.
Ms. Julie Evans	Strategic Analysis, Inc.
Mr. Bob Piccerillo	Strategic Analysis, Inc.
Mr. Brad Smith	Strategic Analysis, Inc.
Ms. Stacie Smith	Strategic Analysis, Inc.
Mr. Theodore Stump	Strategic Analysis, Inc.

ANNEX C.

PRESENTATIONS TO THE TASK FORCE

Plenary Briefings

March 1, 2001

Mr. John Sullivan	CIA Future
Mr. Ken Knight	DIA
Dr. Rick Smalley	Nanotechnology

March 29-30, 2001

Gen Gregory Martin, USAF Commander USAFE	Kosovo Air Operations
LtGen Maxwell Bailey, USAF	Commander AFSOC
LTG Ron Adams	SFOR Commander
ADM Thomas Fargo, USN	CINCPACFLT
RADM Albert Konetzni, USN	Commander SUBPAC
BrigGen William Shelton, USAF	AFSPACECOM
BrigGen Dan Leaf, USAF	Recent Commander 31st Fighter Wing, Aviano AB, Italy
LtGen Joe Hurd, USAF	Recent Commander 7th AF Osan, Korea
MG Dell Dailey, USA	JSOC
MajGen (S) Gary Winterberger, USAF	NATO AWACS Commander

May 3-4, 2001

Mr. Andy Marshall	Discussion

June 28-29, 2001

Hon. Pete Aldridge	USD (AT&L)

July 26-27, 2001

Dr. Dean Kamen	Innovative Invention and the DoD

August 13-24, 2001

Ed Wagamon	Russian Experience in Chechnya
Bob Nelson	Concealment, Deception, etc. in Kosovo
Mr. Luc Barthelet	Computer Simulation and the Sims

Military Applications Panel

May 3-4, 2001

Dr. Delores Etter	DoD S&T Investment Strategy
LTC Bruce Reider, USA	Military Innovations
GEN Wesley Clark, USA (Ret)	Discussion
Dr. Allen Adler	Robotics and FCS
Dr. Ted Gold	Views on Transformation
Dr. Wick Murray	Innovation
Mr. Steve Rast and Mr. Tom Lamp	DARPA UCAV Program
Dr. Douglas Gage	Software for Robotics

June 28-29, 2001

ADM Art Cebrowski, USN	Network Centric Warfare
Dr. Mike Frankel	Telecommunications
RADM R.G. Sprigg, USN	Navy Warfare Development Command “Engine for Transformation”
ADM Bill Owens, USN (Ret)	
MG Bob Scales, USA (Ret)	The Future of Warfare
Dr. George Ullrich	Advanced Weapons: Capability Objectives and Technology

July 26-27, 2001

Mr. Andy Krepenivitch	MilitaryTransformation Implications for Science and Technology
VADM Mayer, USN	JFORSCOM

Technology Panel

May 3-4, 2001

Dr. Greg Papadopoulos	IT
Dr. Joanna Aizenerg	Bio Tech: Biomaterials
Dr. Roger Breeze	Bio Tech: Agricultural Biology
Dr. Gordon Ringold	Bio Tech: Pharmacology
Dr. Patrick Walsh	Bio Tech: Pharmacology
Prof Allan Hoffman	Bio Tech: Biomaterials
Dr. Pat Scannon	Bio Tech: Pharmacology

Technology Panel (continued)

June 7-8, 2001

Dr. Bill Press	Leveraging the Long-Term Defense Technology Investment
Dr. Tom McGill	Today's Lethal MOUT Environment
Dr. Steve Wax	Lightweight Concepts for Personal Protection
Dr. Ephrahim Garcia	Exoskeletons for Enhancing Human Perfomance
Dr. Jordan Pollack	Automated Design of "Throw Away" Robots
Dr. Michael Cima	Ceramic Materials
Dr. Robert Full	Robotic Locomotion
Dr. Michael Macedonia	What the DoD Needs to know (Modeling and Simulation)
Ms. J.C. Herz	Social Ecology of Technological Changes
Mr. Jesse Schell	Massively Multi-Player Games
Mr. Chris Stapleton	Interactive Imagination
Dr. Ken Forbus	AI & Cognitive Science for Use in Military Training
Dr. Stuart Wolf	Potential Impact to Military of Quantum Computing and Communications
Dr. David DiVencenzo	Quantum Computing
Dr. David Awsehalom	Optical Coupling Concepts to Spin Systems
Dr. Eli Yablonovitch	Quantum Device Concepts

June 28-29, 2001

Dr. Paul Kozemchak	Investments and Innovation in the DoD from 1945-2000
Dr. Allen Adler	DARPA FCS Program
Dr. Rodney Brooks	AI & Humanoid Robotics
Dr. Graeme Hirst	Natural Language Processing
Dr. Michael Goldblatt	DARPA

Investment Strategies Panel

May 3-4, 2001

Dr. Delores Etter	DoD S&T Investment Strategy

June 7-8, 2001

Dr. William Rue	System Architecture Experiences from the Business Community
Dr. Roger McCarthy and Mr. John Johnston	Application of Commercial Technologies to the Land Warrior
Mr. John Neer	Commercial and national Security Investment in Space Science and Technology
Mr. Dick Paul	Boeing Perspective
Dr. Robert Hermann	Industry Perspective
Mr. Jack Hammond and Mr. Dale von Haase	Lockheed Martin Perspective
Mr. Wade Schott	GD Perspective

June 28-29, 2001

ADM Art Cebrowski, USN	Network Centric Warfare
Dr. Mike Frankel	Telecommunications
RADM R.G. Sprigg, USN	Navy Warfare Development Command "Engine for Transformation"
ADM Bill Owens, USN (Ret)	
MG Bob Scales, USA (Ret)	The Future of Warfare
Dr. George Ullrich	Advanced Weapons: Capability Objectives and Technology

July 26-27, 2001

Mr. Tom Perdue	Technology Transition

ANNEX D.

MILITARY PRIORITIES QUESTIONNAIRE PROVIDED TO COMBATANT COMMANDERS

1. Briefly describe your current appointment and its operational accountabilities.
2. If you could have your wish/capability right now in your current operational appointment, what would it be? What kind of altered outputs would you want to be able to achieve? In what new ways would you like to be able to employ it and to what effect?
3. What is your toughest/most demanding employment challenge right now? What worries you the most? If that employment challenge could be solved *right now*, precisely what capability would you like to remedy this operational employment deficiency? What are your thoughts as to how it might be employed (conceptually) and to what effect (outcome)?
4. Operationally, where are you most vulnerable? What capability would make a huge difference in mitigating this vulnerability? Think way out of the box…what would *really* make a difference?
5. We have a fair degree (and growing) capability in stealth and a fair degree of precision. How much better does it need to be? How about electronic warfare and the requirement for electronic preparation of the battlefield and enroute support (escort)? Is this an under appreciated deficiency or is it about right…on course? What would you like to have in a more perfect world of instant response that you do not now see coming?
6. How about C4ISR? Given the reality of high demand/low density in certain capability sectors, how could we think of this problem in a different way such that we weren't so reliant on this set of very expensive scarce assets? How about space doing the job? How good would it have to be? What would you as a field commander want C4ISR to be

able to do and on what kind of a timeline? What capabilities would you be comfortable with being exclusively provided from space? Primarily from space? Secondarily/back up in space?

7. Talk about sensor-to-shooter, real or virtual. Given that you would like command-in-the-loop, how would you want sensor-to-shooter to work? How about accountability, recall, etc? What leap capability would materially improve matters?

8. How important is battle damage assessment (BDA) to you? Does it trouble you that BDA is even necessary, tying up assets and perturbing planning/strike cycles? Suppose better, more reliable weapons were available with deadly accuracy? At what point would you be willing to say: with that probability of accuracy and in view of that functional reliability, I don't need BDA; I know it's dead.

9. How satisfied are you with intelligence and geo-spatial (mapping; geodesy; situational awareness) support? How would you like it to be? Be specific. How happy are you with the current capability to deliver relevant intelligence to you, your subordinates/execution cells, and your field units? Is it at the level needed? Be specific. Are intelligence arrangements with coalition partners satisfactory? If not, what would you want to happen to make you more effective?

10. Re mapping and geodesy support. Are you satisfied? Is the necessity for mensuration of targets a problem and inhibitor to rapid targeting/attack/reattack? How good should it be? How about location/height formation (digital terrain & elevation data [DTED])? What accuracy would make a major difference to operational employment (DTED 1 thru 4)?

11. Please discuss command and control. How do you feel with respect to operating inside your adversary's decision cycle? Where are we now? Where would you rather be? Be specific, both in terms of time and capability. Do you think centralized command ad control is best or, in the future, are we better off with a common relevant operational picture at all levels and at all echelons of joint command? In such a circumstance would you go into the "mission orders" business? How about the dark side—the

adversary breaking into the net, either through capture or electronic theft? On balance, where do you want to go?

12. Do you trust your communications/information data links—information assurance issues? How confident are you that we have impenetrable systems such that they can be trusted to execute critical missions on time, on target (synergy/synchronization issues)? In short, if you could have your way, what sort of command and control set up and capability would you want *now* if you could have it?

13. How about information operations: offensive information warfare, defensive information warfare, and information security? Recognizing that no commander seems happy in this area, tell us of your needs, wants, and fears. How do you want it differently? What kind of capabilities at the field level—your level—would really make a big difference in your ability to be dominant and effective? Think big.

14. One final area. How about administrative concerns: personnel matters, documentation, records keeping, data crunching, medical, and other support? Consider in deployed garrision and in field applications, but particularly on the remote battlefield. Do you feel that "support technology" is moving fast enough? Tell us what perfection would be in this area. How you want it to be.

15. Bottom line. If you had to pick 3-5-7-10 (pick a number) technology/capability leap improvements in warfighting, what would they be? Why did you prioritize them as you did? What is so important—outcome wise—and which ones are needed the soonest and why? On the other hand, what capabilities do we now have that you are responsible for and that you think are low contributors to combat outcomes, could be terminated, and the funds rolled into building new capabilities on your priority list?

ANNEX E.

POWER

Electrical power for the military falls into three broad categories:

- Portable power for applications such as communications, computers, and the Global Positioning System (<100 watts).
- Mobile power for applications such as generators, auxiliary power units, and tactical operations centers (kilowatts).
- Stationary power for applications such as bases and ship propulsion (megawatts to gigawatts).

In addition there are many specialized and very challenging applications, for example, individual soldier cooling which requires about 200 watts (W) continuously for extended periods of time. Energy scavenging, or harvesting, from the environment (using power from the sun, wind, and tides) is another niche application, for both small (remote sensors) and large stationary installations.

Advances in large-scale stationary power systems, including the use of more efficient turbines, fuel cells, and potentially nuclear power, are currently be undertaken through both government funding (primarily from the Department of Energy and MITI/Japan) and commercial funding. Cogeneration, enhancements in reliability (e.g., through the development of advanced materials, sensors, and controls) and efficiency (e.g., from operation at higher temperatures or the use of bottoming cycles), and multi-fuel use are all issues currently being addressed. While funding from the Department of Defense might accelerate the search for solutions and demonstrate applicability in specific environments, lack of such funding is certainly not limiting progress at present. Based on the results of the recent Defense Science Board Study on Fuel Efficiency, however, more attention in this area is anticipated.

Similarly, advances in mobile power generation are occurring at a rapid rate due to rising fuel costs overseas. With the advent of new, highly efficient diesel engines in the European automobile and truck markets as well as advanced hybrid power trains developed in Japan and North America, and the current interest in creating fuel cell systems for automobiles and homes, much of the work in mobile power systems is

already being conducted without significant funding from the DoD. It is estimated that in 2001 over $1 billion of venture capital funds will flow into the energy sector. These new systems offer smaller, lighter, and more efficient operation at lower cost and with less environmental impact than ever before.

The commercial market is already pursuing issues such as rapid start-up, acoustic and thermal signatures, operation in extreme environments (e.g., temperature, humidity, altitude), environmental emissions, cost, and reliability under adverse conditions due both to government mandate (particularly in Japan and Europe) and to enhanced consumer interest. In many cases military specifications for such power systems are no more stringent than those imposed by the automobile industry. The key for the DoD is to ensure that such systems will operate on fuels found worldwide (e.g., logistics fuels) which are generally not as clean or as well refined as those found in North America, Japan or Western Europe. Thus, funding for fuel reformers, multi-fuel systems and systems integration may be an appropriate DoD contribution.

The biggest power challenge facing today's military is in portable power sources. The impact of this issue is graphically demonstrated in Figure E-1, where a weight trade-off between batteries and other mission-critical items is shown. Anecdotal remarks from soldiers indicate that they sometimes take less food and water on a mission in order to carry more batteries. Due to the proliferation of battery types and sizes in use (which number in the thousands across the DoD), resupplying batteries in the field is even more difficult and probably more expensive than resupplying fuel. Note that while the cost of fuel at a depot is less than $1.50 per gallon, the estimated cost on the front line is in excess of $500 per gallon. To date, a similar analysis has not been performed to access the cost of delivering batteries to soldiers in battle.

Although substantial advances in battery technology have occurred over the last few years, improvements in energy density have come only at the rate of about 5 to 10 percent per year. This rate pales in comparison to, for example, Moore's law. One major advantage of the breakthroughs in microelectronics is that the power usage per transistor has dropped dramatically over the last two decades. Unfortunately this drop has been more than offset by the increase in the number of transistors in any given device, which has grown orders of magnitude faster. Thus today's microprocessors can require upwards of 100 W of power. This gap between the need or demand for the function of the device and the ability to supply power in a compact form is continuing to grow. Thus as the size of individual microelectronic components continues to shrink, the weight

and volume of the power source can dominate the system. Figure E-2 shows the component breakdown of a typical cell phone.

Figure E-1. Today's weight trade-off: Adding electronics and batteries is at the expense of other mission-essential items.

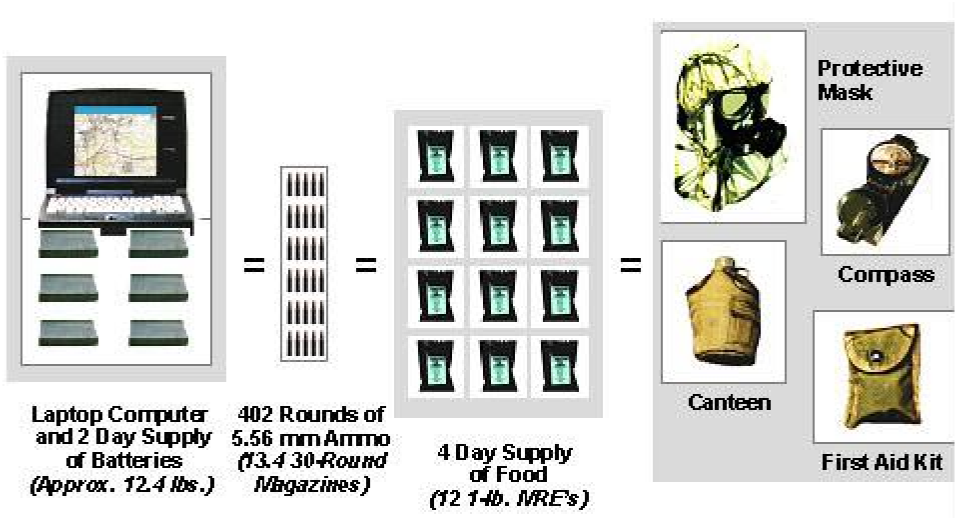
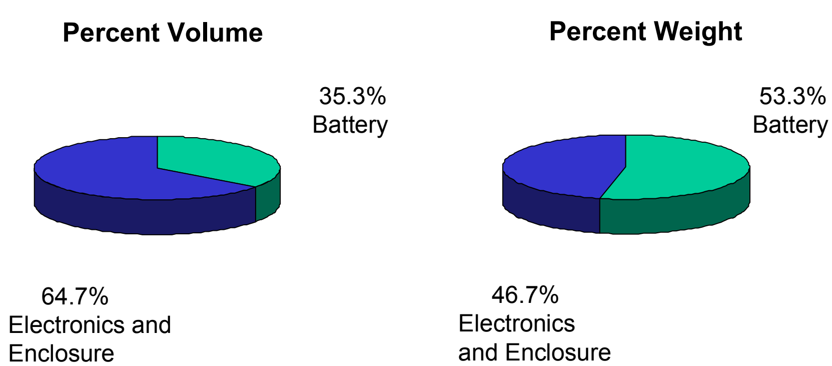


Figure E-2. Batteries are clearly the size and weight drivers for portable electronic devices as evidenced by this data from a Motorola Micro TAC Lite cellular telephone.



Despite the large role that today's batteries play in portable electronic devices, there is minimal commercial or government investment in "leap ahead" battery technologies. Current improvements (particularly advances in lithium and lithium-ion rechargeable batteries) are completely driven by the commercial sector, with the Japanese and Koreans in the lead. There

are a few new ideas for improved anode, cathode, and electrolyte materials, but these developments would provide less than a factor of two increase in performance. The Army is looking for almost an order of magnitude improvement in performance in the next 20 years (see Table E-1).

Table E-1. Land Warrior Operational Requirements Document, August 3, 1999 (Scott Feldman, Natick Soldier Center, Natick, MA).

	Units	Baseline (1998)	2003	2005	2008	2018- 2125
Average Power	Watts	23	16	8	4	2
Energy in 12.5 hr	W hr	285	205	95	51	26
Mission Duration	hrs	12.5	12	48	72	227
Mission Energy	W hr	285	197	364	294	455
Mission Weight	lbs	5.9	1.6	2	1	1
Energy Density	W hrs/kg	106	271	400	646	1000

The intelligence community is the only part of the government providing relatively modest funding on more advanced battery systems. The word system must be stressed here. This community deals with a very uneven duty cycle in many applications and is therefore considering "hybrid" battery-battery or battery-ultracapacitor systems. In battery chemistry there is generally a trade-off between high energy density and high power density. For example, today's best rechargeable lithium ion batteries have energy densities on the order of 120 W-hrs/kg and can deliver about 100 W of power. In contrast, an ultracapacitor (electrochemical double layer capacitor) holds only about 20 W-hrs/kg, but can deliver several kilowatts/kg. Combining a low-rate, high-energy-density battery with a high-rate ultracapacitor may provide the best combination of performance features for many applications. For example, a digital cell phone on standby for an extended period of time requires very low power, but a lot of energy. In talk mode the power requirements are high, but the duty cycle is short, so that the energy needs are generally low.

Clearly, to address the challenge created by high-power electronics, technologists can work either to drop the power requirements of the system dramatically, to improve the performance of the power source to meet new demands, or to do both in combination. Both avenues are certainly being pursued. The commercial sector is currently the driver for

low-power electronics (though much of the current work can be traced to earlier programs funded by the DoD). Consider, for example, the size, weight and run time of a state-of-the-art cell phone (days) or how long the battery lasts in a new personal data assistant (weeks). The use of low-power microprocessors, more efficient displays, and advanced power management tools allows laptop computers to run for up to eight hours. The DoD recognizes these gains (see Table E-1 above) and will certainly leverage the efforts of others. These gains will also help to solve the soldier backpack weight problem. Although significant advances have been made—next generation SINGARS radios are less than 1/10 the size [548 in3 vs. 48 in3] and 1/7 the weight [3 lbs. vs. 22 lbs.] of current models, for example—there is still substantial room for improvement. SINGARS radios are still more than 10 times the size and weight of even a low-cost cell phone.

Some of the most popular current and potential future battery chemistries are summarized in Table E-2. Most very-high-energy-density systems are experimental or require an open system (e.g., they use air or water from the environment at the cathode). The energy density is deceptive since no (or minimal) cathode materials need be factored into the weight of the cell. As can be seen in Figure E-3, the cathode dominates the size and weight of a typical electrochemical cell. Open systems, however, become heavier as usage increases due to the formation of product salts at the cathode. For the most part these salts are quite inert and can be "dumped overboard" as the system discharges. As the cell sizes shrink, the current collector and packaging size and weight becomes a greater fraction of the overall system size. Nevertheless, low-rate metal-air systems are practical for hearing aid batteries. Zinc-air systems have recently been introduced into the cell phone market with limited success. Most open systems are far more experimental than their sealed counterparts, and energy densities of practical systems are hard to estimate since once a battery is "started," it cannot be stopped. Note that sealed systems are particularly important for underwater and space operations.

An interesting observation from Table E-2 is that the practical energy density of a cell is only about one-quarter of that of the maximum theoretical energy density. This is due to packaging, binders (inactive materials), current collectors, and "unknown factors." (See Figure E-3.) The relative contributions of each of these factors varies dramatically depending on the size, power requirements, and geometry of the cell.

Table E-2. Energy densities of some common and experimental battery systems.

Couple	Common Name	Voltage (V)	Maximum Specific Energy (Wh/kg)	Practical[1] Specific Energy (Wh/kg)	Practical[1] Energy Density (Wh/L)
Sealed Systems					
Cd/HgO	MerCad	E^o = 0.922	142	65	300
Pb/PbO_2	Lead-Acid	Voc = 2.18	182	34 [2]	85 [2]
Cd/NiO(OH)	NiCad, Nickel-Cadmium, Ni-Cd	Voc = 1.30	210	34 [2]	100 [2]
MH/NiO(OH)	Nickel/Metal-Hydride, Ni-MH	Voc = 1.35	220	54 [2,7]	180 [2,7]
Zn/HgO	Mercury-Zinc	Voc = 1.35	242	100	360
$Zn/alk/MnO_2$	Alkaline Manganese	Voc = 1.55	302	140	365
Zn/AgO	Silver-Zinc	Voc = 1.82 & 1.56	435	90 [2]	170 [2]
				220	850
Li/I_2	Lithium/Iodine	E^o = 2.78	555	260 [3]	940 [3]
LiC_6/Li_4CoO_2	Lithium Ion	Voc = 4.00	455 (630)	125 [2,7]	300 [2,7]
Li/MnO_2	Lithium/Manganese Dioxide	Voc = 3.15	900	280	600
Li/SO_2	Lithium/Sulfur Dioxide	Voc = 2.95	1110	300	500
				260 [4]	350 [4]
Li/FeS_2	Lithium/Iron Disulfide	Voc = 1.80 & 1.60	1230	260 [8]	480 [8]
$Li/SOCl_2$	Lithium/Thionyl Chloride	E^o = 3.70	1490	510	1020
				660 [5]	1200 [5]
Li/CF	Lithium/Carbon Monofluoride	Voc = 3.00	2120	290 [9]	510 [9]
				600 [6]	1000 [6]
				820 [10]	1180 [10]
		E_H = 4.5	3200		
Li/Cl_2	Lithium/Chlorine	E^o = 3.98	2520		
Li/S	Lithium/"Sulfur"	Voc = 2.20	3680		
Li/SRIF [11]		E^o = 5.8	4750		
Open Systems[12]					
Mg/Air		E^o =3.1	6800		
Al/Air		E^o = 2.7	8130	300	330
Zn/Air (cell phone)		E^o=3.6		150	
Li/Water		E^o = 3.1	8530		
Li/Air		E^o = 3.4	13,000		

Voc is the measured open circuit voltage

1 Based on "D" volume cells unless otherwise noted

2 Rechargeable cells

3 Heartpacer cells, 37oC

4 Army version (higher rate capability)

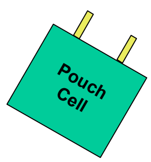
5 10,000 Ah, low rate cells (obsolete)

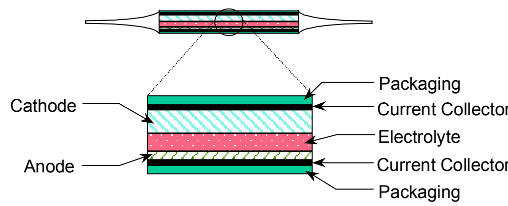
6 GJM 3/88 "DD" cells
7 "4/3A" cells
8 "AA" cells
9 Commercial "C" cells
10 GJM 1,200 Ah (low rate design)
11 SRI proprietary cathode material, all values are estimates
12 Maximum specific energies are based only on the weight of the anode material

Figure E-3. Weight breakdown of a typical sealed cell.

Weight Breakdown of a Conventional Lithium Battery

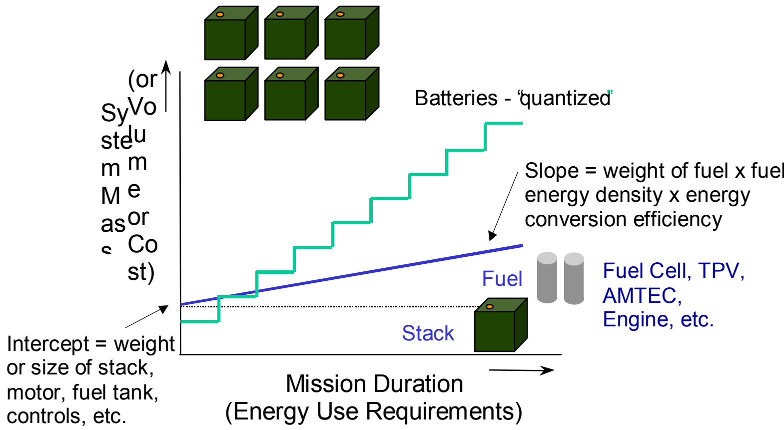
current collector	2.7 g
anode	0.5
electrolyte	3.0
cathode	10.3
current collector	2.7
TOTAL	19.2 g (plus packaging)





While today's small-scale systems use energy storage devices, larger-scale systems convert hydrocarbon fuels (or, in very large systems, nuclear fuel) to electrical energy. At present both the Department of Defense and commercial industry are pushing to develop compact energy conversion devices to run radios, cell phones, laptop computers, and the like. There are a number of issues that must be addressed, however. The most important consideration is the details of the mission—short vs. long, continuous vs. intermittent duty cycle, maximum and minimum power requirements, etc. As shown in Figure E-4, for short missions, batteries or extremely small energy conversion devices (e.g., microturbines) may be the best option to provide power, but for longer missions the size, weight, and cost of the power source are dominated by the respective size, weight, and cost of the fuel. In this case the energy density of the fuel and the efficiency of energy conversion are key parameters.

Figure E-4. The trade-off between energy conversion devices and energy storage devices.



Government funding in the small power source area is really focused on energy conversion devices (fuel cells, small engines, etc.) with very little funding going into "really advanced" batteries (i.e., heavily fluorinated systems, metal-air and metal-water chemistries, see Table E-2). Primary sources of funds include the DARPA Palm Power Program and NIST ATP. There is also growing interest in this area from the Department of Energy. The driving force here is the very-high-energy-density of many fuels.

For example, methanol has an energy density of about 5600 W-hrs/kg, nearly 50 times that of a rechargeable lithium ion battery. Butane is more than twice as energy-dense as methanol, logistics fuel (e.g., diesel or jet fuel) is 2.5 times denser than methanol (about 13,000 W-hrs/kg), and the energy density of hydrogen is a whopping 30,000 W-hrs/kg. On a per weight basis, even 1 percent energy conversion of hydrogen leads to a system substantially better than the best batteries in use today.

Unfortunately even liquid hydrogen is not very dense (about 71 g/liter), which means that the practical energy density of hydrogen is only ~2100 W-hrs/liter. Hydrogen can be stored at a density that approaches that of liquid hydrogen and is on the order of a few percent (see Table E-3). There is work currently being conducted on the use of chemical hydrides such as MgH2, LiAlH4, alkyl silanes and amino boranes to generate hydrogen in situ, but issues of control, generation rates, and safety (e.g., chemical stability, thermal runaway) have yet to be solved

completely. [Note: experimental evidence indicating >>10% by weight hydrogen storage on graphite nanofibers have never been reproduced.] Throw in the size, weight and cost of a fuel cell (or other energy conversion device), and the efficiency of energy conversion (~10 - 50%) and one can see why people aren't yet jumping all over even hydrogen-powered systems for portable devices. Restrictions are eased somewhat as the size grows due to the approximate fixed size of the control electronics and some of the packaging as well as the ease of storing high pressure gaseous hydrogen in larger tanks.

As shown qualitatively in Figure E-4 and quantitatively in Table E-3, fueled systems make the most sense for the longest missions where the weight and size of the energy conversion device and the fuel tank become negligible compared to the weight of the fuel, the energy density of the fuel and the efficiency of energy conversion. Fueled systems also make sense where issues such as acoustic and thermal signature, start-up time, and air independent operation are not key concerns. For example, internal combustion engines or microturbines, which tend to be small, lightweight, and provide high power, but which are inefficient, noisy, and hot may make sense to power micro-air vehicles.

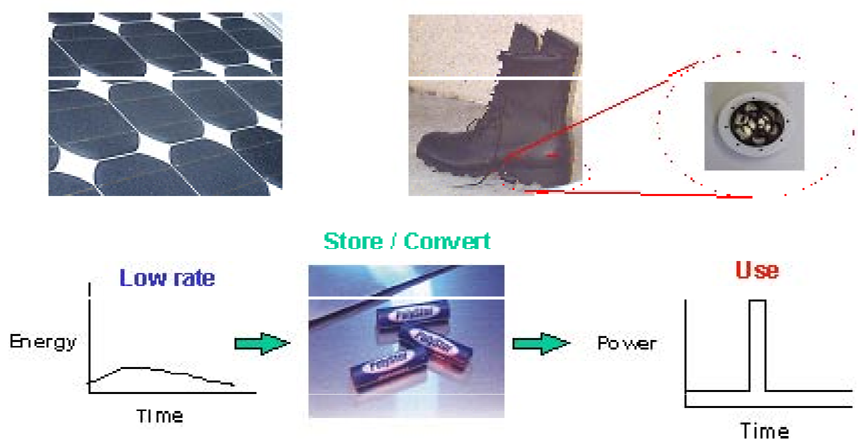
One area that has not received much attention from the DoD is small (portable) nuclear sources. While such systems have been used in space exploration for years and have racked up an impressive reliability record (over 250,000 hours of operation without a single failure), terrestrial applications (other than niche applications such as powering pacemakers) have not been forthcoming. Clearly public perception is a big issue, although unbeknown to most, small radioactive sources are present in smoke detectors, emergency exit signs, and other common items. Although the energy density is quite high due to the long lifetime of the source, most radiation-based systems tend to have quite low power densities. (Shielding is typically very heavy.) To date no serious research effort has been directed at how to build and optimize these devices. Expanded funding by the DoD could make a significant impact in this area, particularly in the development of sources better matched to energy conversion materials (typically thermoelectrics) and in packaging and shielding.

Table E-3. Approximate energy density of small energy conversion devices and fuels.

	Energy (kWh)	Energy Density (Wh/kg)	Power Density (W/kg)
Current/Near Term DMFC, 60W	1.44	215.4	9.23
	4.9	553.8	6.59
3-5 yr Advanced DMFC, 20W	1.6	1558	19.05
	5.06	2300	9.1
Theoretical Energy Density of MeOH		5600	
Current/Near Term PEM Fuel Cell	1.6	235	14.67
5000 psi compressed H2, 100W	4.8	377	7.85
	10	447	4.47
1-2 yr H2/PEM, 100W (10-12% by weight H2 storage)	1.6	256	16.08
	4.8	439	9.13
	10	537	5.37
Advanced (3-5 yrs) Solid Oxide Fuel Cell, JP-8, 20W	1.44	1506	20.9
	4.87	3200	13.2
	10	4235	8.4
Thermoelectrics (BiTe TEG operating at 4.5% efficient heat to electricity)			16
Thermal Photovoltaics (TPV, 20W at 2% efficient fuel to electricity, butane fuel)			
Alkali Metal Thermal Energy Conversion (AMTEC)			
Current, butane fuel (~10% efficient fuel to electricity)	1.46	502	6.9
	5.2	760	2.9
	10.4	842	1.6
Future, butane fuel (~15% efficient fuel to electricity)	1.4	598	8.5
	5.2	1032	4.0
	10.3	1195	2.3
Advanced (3-5 yrs) ICE/MicroStirling/Turbine, 20W	1.44	2900	40.3
	4.8	3532	14.75
	10	3711	7.4
MIT microturbine project (goal: 5% efficient conversoin of butane to electricity)		600	
Theoretical Energy Density of Diesel Fuel		~13,000	
Nuclear			
Current pacemaker “battery” (PuO2/BiTe), including source and shielding			0.02
Space power (SiGe TEG, 0.07% efficient), including shielding			5.3
^{90}Sr + Icosohedral Boride, 1% efficient energy conversion		~100,000	
28 year half-life, no shielding required for small systems			

Finally, no discussion of power sources for the military would be complete without at least a brief mention of energy scavenging techniques (especially solar and thermal). While these technologies may not provide the needed energy or power by themselves, when coupled with batteries and/or ultracapacitors they may provide a good solution for systems requiring long duration and very low or intermittent power (see Figure E-5). There is certainly a lot of work being pursued in this area, most of it outside of the DoD (at, for example, NREL and MITI/Japan).

Figure E-5. Energy generation from an array of solar cells or a "power boot." Energy scavenging is typically a low rate process requiring a battery or ultracapacitor to store or convert the energy to a useful form.



Solar cells are particularly useful for low-power applications (one can already buy solar-power calculators and watches or "power boosters" for cell phones, for example). For anything that requires serious power, size becomes an issue. For example, a small laptop computer requires 30 W of power. At 23% solar to electrical energy conversion efficiency (typical of very high-end single crystal silicon), a panel of 15" x 15" exposed to direct sunlight at noon is required to be effective. (About 1 kW per m^2 of sunlight is about the maximum that hits the earth.) At other times of the day (or with clouds, at night, indoors, etc.) a much larger array would be needed. Having said that, using a solar panel to keep batteries topped off will certainly extend the life of a system. Optimizing the mix of batteries for continuous duty operation with ultracapacitors for intermittent power needs (e.g., starting the hard drive of a laptop computer) will also improve

system life. Other alternatives include wind-up power (commercially available for radios and flashlights), the "power boot" being developed by DARPA (power generation through walking, see Figure E-5) and thermoelectrics (TEGs) for powering distributed sensors (DARPA/Office of Naval Research) funding.

As one looks further out into the future, there are many wildcard technologies that may or may not be practical sources of energy for the military. These include molecular motors, biofuel cells, solid-state engines, "cold fusion," microemitter arrays, sonofusion, and many others. In addition, there are potential breakthroughs in power distribution technologies such as lightweight, low-cost plastic conductors, room-temperature superconductors, and energy "beaming." The DoD can either take a leadership role in these areas and make a substantial impact on our future, or just track developments as they unfold with an eye toward capitalizing on possible breakthroughs.

It is very clear from the above that there is no one single solution to all of the power problems facing the U.S. military (other than dropping the power needs of specific devices, which is already happening). Further, despite best efforts, power requirements in the military are likely to grow in the future (e.g., due the need for increased soldier microclimate cooling in response the growing threat of chemical and biological weapons or the development of advanced electric battlefield vehicles and the use of directed energy weapons). Of course the military has certain requirements that most civilians do not need to consider (e.g., extremes of temperatures (-20 to -60^{o} C) and operation in space or under water. These requirements almost certainly mean that some sort of energy storage device will be required, independent of whether one uses a fuel cell, small generator, or solar cell.

ANNEX F.

BACKGROUND AND CURRENT ASSESSMENT OF UNMANNED GROUND VEHICLE TECHNOLOGY

Unmanned aerial platforms are a visible mainstay in current U.S. operations. They are likely to remain so for the foreseeable future. As a result, the technology and capabilities of such platforms are widely understood throughout the defense establishment. Unmanned underwater platforms are less so, but also less likely to play a defining role in overt military operations. This said, there is great interest in the active use of unmanned ground vehicles, which presents some important technological challenges. These challenges and some of the DoD's programs to address these challenges are described below.

Unmanned Ground Vehicles

Research and development related to mobile robots has been conducted over the past 40 years. Currently, approximately \$60 to \$80 million of R&D is being spent annually by the DoD in this area. To date few mobile robots have been added to the military inventory. Those that have are primarily used for performing dangerous missions such as explosive ordnance disposal or mine field clearing. These robots are characterized by their relatively large size and their teleoperated brute force approach to mission success. In the past couple of decades, as the result of increased computation and sensing capabilities enabled by microelectronics and MEMS technology, emphasis has focused upon the development of robots for surveillance and reconnaissance missions. Much smaller size, with on-board sensing, communications, and processing characterize these robots.

Large Robots. The United States Marine Corps in coordination with the Unmanned Ground Vehicle Joint Program Office, has developed and transitioned to acquisition a Standardized Robotic System that is basically a kit that allows currently fielded vehicles to be retrofitted for teleoperation. Vehicles such as a D7G bulldozer, an M1 main battle tank chassis, a HMMWV and an M-60 tank chassis have been teleoperated to conduct breaching, route clearing, and area clearing missions. The Office of Special Technology has developed a mini-flail system to clear anti-personnel land mines. As a result of this effort the Engineering School

developed a requirement for a 300 meter line-of-sight vehicle able to neutralize anti-personnel landmines, perform wire breaching, dispense obscurants, emplace demolitions, sweep runways, and create access lanes through buildings or other antipersonnel obstacles. It is scheduled to reach production in fiscal year 2005. Other large robots include the All-Purpose Remote Transport System capable of remote operations in various mission profiles, including clearing unexploded ordnance, and the Automated Range Ordnance Mapping System, to retrieve buried ordnance and other hazardous items.

Medium-Sized Robots. The DARPA Tactical Mobile Robots program has invested approximately $50 million over the past five years and has developed a variety of new robotics technologies and platforms designed for dismounted operations by projecting operational influence and situational awareness into previously denied areas. The robots range in size from those that can be thrown to robots that weigh 30 to 60 pounds. The stated technical objectives of the program are:

- Machine Perception: Provide multi-sensor hazard detection at 20 Hz, non-GPS position estimation, and multi-source topological mapping with 90% accuracy.
- Autonomy: Demonstrate robust traversal of complex terrain with minimal (less than 1 command per 50 m) human supervision. Develop and implement self-recovery behaviors (self-righting, anti-handling, etc.) that compensate for unanticipated events.
- Mobility: Negotiate complex obstacles (stairs, rubble, etc.) and barriers (barbed wire, fences, etc.) with greater efficiency and less operational risk than human-oriented alternatives.
- Human-Robot Interface: Create a non-distracting, alert-based system that allows a single operator to task, control, and interact with no fewer than three different platforms simultaneously.
- Collaborative Robotic System Integration: Employ a collaborative team of multiple robots that cooperate to perform complex missions that exceed the capabilities of any single platform. Develop and demonstrate collaborative semi-autonomous behavior (docking, power exchange, partner inspection, etc.) that allows teamed platforms to function reliably in adverse conditions.

Miniature Robots. The DARPA Distributed Robotics program has developed a variety of miniature robots that are approximately one inch to five inches in size. Mobility modes such as wheels, tracks, jumping, climbing, slithering, and swimming are being developed. One robot was designed to be shot from a M203 Grenade Launcher through a building window and then be teleoperated through a building using wheeled locomotion and sending live video back to an operator outside the building. This robot also has a spring-operated foot that allows the robot to jump and potentially climb stairs. Another robot was developed with a vortex generator that allows the robot to be attached to a vertical surface and climb upward. It can also travel along ceilings. Also developed were robots that can change shape from a track to a snake to a legged robot. Working with the DARPA Software for Distributed Robotics program, algorithms and networks are being developed to allow multiple miniature robots to operate collaboratively to accomplish a specific mission. Other DARPA programs are investigating biomimicry for robot locomotion and control.

Miniature robots are appealing because they are portable, cheap, have reduced visible and acoustic signatures, can be owned and operated by individuals in a small team, and can perform tasks that larger robots or humans can't perform. Experiments with operational forces have validated their strong appeal and military applicability. Research and development in miniature mobile robots is relatively new and has been driven primarily by the entertainment industry, which is producing toys with greater and greater sophistication. Lego, for example, has developed a kit from which children can build a wide variety of robots. The modular approach allows flexibility in platform design, selection of a variety of simple sensors, alternative uses of motors for locomotion or actuation and a simple user language that allows children to program robot behavior on a PC and automatically download to the robot via infrared communications. These robots are very crude, mechanically fragile, and offer little utility for military operations.

Miniature robots, however, offer great promise for future military operations. Used in a system in conjunction with other robots, unmanned air vehicles, unmanned ground sensors, and small teams, miniature robots can add value in unique ways. Their primary contribution in surveillance and reconnaissance missions is their ability to get close to a target and either provide high-resolution information about the target or serve as a sacrificial target designator. They can also be used in a manner similar to unattended ground sensors. But by moving they can gain better surveillance vantage points or improved signal transmission/reception positions. Operating in collaborative groups they can gather information

over large areas and transmit target information along with coordinates to a central location for compiling into a comprehensive situational awareness system. Moving also allows robots to calculate relative target positions. Miniature robots can be propelled into buildings, conduct searches, and transmit real-time information back to operators.

The key to successful robot design, development, and transition to operational use has been to focus narrowly on a specific mission where the value-added offsets the high cost of low-volume production. The key to future robot success will be the ability to develop small robots with modular designs that can be inexpensively and rapidly tailored to meet specific mission needs. In general, the demand for deployable robots that can gather, process, and communicate information is limited by the lack of technology and appropriate tactical thinking about the effective use of robots for small-team operations.

Because a robot is essentially a system that operates within a system, technical progress needs to be made in several challenging areas. These areas are mobility, communications, navigation, sensor integration, sensor and information processing, autonomy, collaboration, power, and human-computer interfaces, all within the context of relevant military missions.

Mobility

Novel locomotion mechanisms for small robots to move toward an objective and avoid or overcome obstacles are needed. Small motors offer optimum efficiency when rotating at high speed. These speeds are orders of magnitude higher than wheels or tracks can accommodate. Coupling the motor speed to wheel or track speed requires either dropping the applied voltage or employing reduction gears; both methods result in drastically reduced efficiency.

Small robots need to be fast and at the same time have high torque to enable them to overcome obstacles or ascend inclines. Current motors that are optimized for high speed exhibit low torque; high torque implies low speed. New motor concepts that offer small size, high speed, high torque, and high efficiency at the robot platform level are needed. Wheeled robots typically cannot overcome obstacles that are larger than approximately one-half the diameter of a wheel. Other forms of locomotion have similar constraints. Combinations of multiple forms of locomotion that include, for example, wheels (good for smooth surfaces), tracks (good for rougher terrain), jumping (good for overcoming obstacles), slithering (good for uneven terrain), climbing (good for vertical surfaces) or other novel ideas that allow movement in unstructured

environments are needed. A small general-purpose robot that is able to traverse all forms of terrain is probably not feasible.

Communications

Since no fully autonomous robots will exist in the foreseeable future, communicating to and from robots is essential to both control and receive sensor information. Several modes of communications are needed. Teleoperation requires signals from an operator to the robot at speeds sufficient to obtain the desired performance. Some semi-autonomous behavior is enabled by providing a robot waypoints and then allowing the robot to find its own way without supervision unless it gets into trouble. The robot must transmit sensor-derived information back to an operator.

When collaborating with other robots, networked communications among the robots is needed. A variety of communication modes have been employed including acoustic, radio frequency (RF), and optical. Acoustic methods have limited operating range, multipath and noise. RF systems have difficulty with ground coupling, multipath, and jamming. Most robot developers seek inexpensive methods for communications and typically use 800-to-900-MHz miniature transmitters or receivers or 1.2 GHz wireless local area networks that are commercially available and usable without the need for Federal Communication Commission licenses. A common problem with these radios is that potential adversaries easily intercept their signals and they are easily jammed.

Frequency stomping has been a problem in the conduct of field experiments with operational forces when multiple robot contractors are all trying to operate simultaneously on the same frequency. Optical communications have also been used. This approach suffers from problems caused by light scattering, reflections, and transmission in rain or fog, and it presents problems with aiming a beam between moving robots or people. More robust communications approaches are available but their size, weight, power requirements and available bandwidth precludes their use in small robots. Significant investment in the telecommunications industry (cell phones and wireless networking) is driving the technology in the right direction, but characteristics like wide bandwidth, security, antennas, and low cost are not yet available for use on miniature robots in military environments.

Navigation

Most robots are teleoperated. They navigate by remote control with an operator issuing commands while watching the robot. Cameras on robots

can be used to provide location information to an operator when the ability to physically see the robot is otherwise obstructed. If pre-knowledge of the terrain exists, route planning can be used to program a robot with waypoints. In this case, robots must know when they reach a waypoint so they can change direction. Dead reckoning has been used by counting wheel turns, but this approach suffers from problems of accuracy, especially if wheels slip when traversing loose sand, or mud, or rubble. Global positioning can be used when operating in areas that have clear access to satellites. But GPS may only be intermittently available when operating in urban canyons or inside buildings. Also, accuracy becomes an issue when using commercial C/A code unless time is available to establish differential sites. Military-accuracy GPS devices are typically too large for use with small robots. Inertial navigation devices (combinations of gyros and accelerometers) have been used to provide six-degree-of-freedom positioning data. However, the state of accelerometer technology allows navigation accuracy for only very short periods of time (minutes). Cooperative navigation can be employed using active mechanisms such as lasers, radio frequency, and acoustic sources to range, triangulate or use time-difference-of-arrival methods to determine robot positions. These mechanisms are less covert because they emit energy into the environment. They also typically require direct line-of-sight.

Sensor Integration

Sensors are an essential component in any mission-oriented robot. Sensors are needed to provide real-time feedback to its control system or to an operator. Simple sensors such as proximity sensors, acoustic sensors, and cameras have been used for this purpose. Sensors are also needed to obtain information about targets of interest in the environment. Military operators desire the ability to place all of their personal sensors (eyes, ears, smell, feel) at a remote location of interest without physically being collocated.

The most attractive sensor is the video camera, because it provides the greatest amount of information in the shortest amount of time. A single camera can assist in teleoperation as well as provide information about targets. A wide variety of other sensors can be employed to detect the presence of specific physical (temperature, pressure, light, vibration, etc.), chemical, or biologic substances. Since none of these sensors have been developed specifically for application on small robots, their use requires mechanical and electrical tailoring for physically mounting and functional operation.

Useful available sensors have a variety of deficiencies. Sensors typically require a large aperture to achieve maximum signal collection. Available sensors tend to be too large for small robots. Shrinking the size of the sensor also shrinks the collection area and, while it still can perform its intended function, its robustness declines proportional to the area reduction. Also, there exist no standard interfaces for sensors. Every different sensor has its own unique input/output characteristics that result in unique system hardware and software interfaces.

A robot needs multiple sensors to determine information about its own state, to assist in navigation, and to obtain target information. The physical placement, interface requirements, and on-board networking approaches present a complex design task that must also consider the minimization of overall robot energy requirements. The positive identification of a target of interest is dependent upon the physical, chemical or biological signatures of the target.

There is no sensor that can automatically positively detect and identify a human, for example. It is only through a combination of data obtained from multiple sensors about the known characteristics of a human that a probability can be assigned to the automatic detection or identification of that human. Incorporating a suite of sensors with an acceptable composite fidelity, dynamic range, and environmental ruggedness into a system with stringent size and power constraints requires the development of novel design philosophies, architectures, and tools that are focused on tight integration.

Sensor and Information Processing

Since sensors react to physical, chemical or biological stimuli and typically provide this data in the form of voltages or currents, some form of processing is necessary to translate this data into information. Many companies incorporate some form of signal processing in the sensor product; others simply provide the sensing mechanism. It is therefore possible that a robot with five different commercial off-the-shelf sensors could also have five separate signal processors, each of which is tailored to a sensing mechanism. Robots with multiple sensors need to address the size, power, and cost trade-off of using a variety of sensor and signal processing products or multiplexing raw sensors with a single signal processor. In any case, the output of first-stage signal-processed data is insufficient to make acceptable decisions about the object being sensed.

Sensor data needs to be fused into a more comprehensive representation the object being sensed. While significant progress has been made in sensor fusion technology, the processing requirements are

complex and typically require computational power in excess of what could be reasonably incorporated in a small robot. If this is true for a specific mission scenario, then the sensor data could be transmitted to a central location for processing. In addition, if multiple robots are being used to accumulate data from a wide-area search, then it is highly likely that each of the robots would transmit its findings to a central location. This, however, requires communication channels with adequate bandwidth that perform within the constraints mentioned in the communications section above.

Autonomy

A perfect robot or system of robots would be capable of accepting a mission level command, similar to what one person would instruct another person to do (search that area for evidence of explosives and render helpless any that are found), and then carry out its mission with high probability of success and no human intervention. We are decades away from even approaching this level of autonomy.

Intelligent-like behavior can be demonstrated through a combination of sensors and processing. There are four distinct levels to consider. The first level is for internal control of the robot, which involves coordinating the actions of motors, gears, flaps, and the like for locomotion and understanding the robot's internal state. The second level involves coordinating on-board sensors that sense and interrogate the external environment for the purpose of navigation. The third level involves coordinating on-board sensors to detect, identify, and/or decide about mission-related objects (targets). The fourth level involves collaborating with other robots to achieve the mission.

Most robot developers have a good understanding of how their robots are internally controlled. Upper-level commands are typically translated into voltages by a processor and digital-to-analog converter to control the speed and direction of motors which in turn control wheels, tracks, leg extensions, or other propulsive parts. In some cases, sensors that sense the state of the robot (wheel rotation, leg extension, flap position, etc.) provide feedback to a processor to adjust robot performance. Internal control also includes the hardware and software required to achieve reconfiguration to a different locomotion mode (e.g., track to snake).

Internal robot control and mechanical and electrical designs are tightly coupled. During the typical development process, trade-offs are constantly being made by adding additional software to execute better control or to change mechanical and electrical designs. Optimization for efficient operation is effected after first prototypes are fabricated. Care

must be taken to assure that the robot uses minimum energy for mission success. Non-optimized hardware and software designs can consume excess power and leave little energy available for mission-related sensors, processing, and communications. On a small robot, the controller is typically an 8-bit processor (PIC) operating at 20 MHz with 8k of ROM code and 192 bytes of RAM. One processor is usually dedicated to motor control. A second processor serves as a central manager by parsing incoming messages and handling any local behaviors.

A second level of intelligent-like behavior involves understanding the immediate environment to allow the robot to make decisions about where it is currently located and to move to a different location. A third processor is typically used to coordinate the sensor information and provide this to the central processor. There are two distinctly different approaches. The first includes using some form of navigation aid such as GPS, inertial navigation, loran, or dead reckoning (counting wheel rotations and compass readings after leaving a known location). In this approach, the robot knows its current location and is provided with waypoints to travel to a different location.

While progress has been made in these technologies, each have deficiencies and none of them is adequate for operational use with mission times greater than tens of minutes. The second approach involves executing degrees of local behavior like obstacle avoidance, wall following, homing and follow the leader. They derive their knowledge of the environment from simple sensors (touch, pressure, temperature, acoustic, semiconductor lasers, RF or LED rangefinders, LED communications, and cameras) and progress along a pre-programmed path or seek local maximum sensor inputs.

The third level of intelligent-like behavior involves gathering information associated with the mission. This includes capturing images or video or sensing the presence of a target of interest (people, vehicles, weapons, chemicals, bio agents, explosives, etc.) by using a combination of sensors such as acoustic, temperature, pressure, or vibration. This is a very complex task for a small robot. It involves interrogating a sensor suite, potentially fusing sensor data, processing raw data into information, and making decisions about thresholds. It involves detection, classification, and identification. While a significant amount of R&D is being conducted in this area, the ability to incorporate an adequately sophisticated set of of sensors and high-speed processing on a small robot is beyond current technical capability. Small robots can, however, sense raw data and communicate to a central processor capable of analyzing and deciding and then communicating reaction information back to the robot.

The use of many distributed robots (mobile sensor platforms) can add significant value to a surveillance or reconnaissance mission.

The fourth level of intelligent-like behavior is exhibited through collaboration and control of multiple small robots. Little progress has been made in overcoming significant technical barriers to collaboration. These barriers are primarily associated with communications and networking. Small robots operate close to the ground and communications are limited to short ranges (10 to 100 meters) because of ground coupling, multipath, small available antenna volume, interference, and power requirements associated with transmit and receive duty cycles. Networking solutions that try to overcome communication limitations result in large processing delay times. While progress is being made in this area, the current state-of-the-art for small robots results in effective behavior at the expense of time. So, while the overall robot group can perform a task, the extended time consumed make the group appear to be sluggish or slightly stupid.

The intelligent behavior of a robot and therefore its level of autonomy is difficult to characterize quantitatively. This is primarily because the definition of human intelligence and autonomy suffers from similar difficulties. Intelligent-like behavior requires a systematic coordination of multiple sensing modalities, sensor- and application-specific signal processing, decision making in unstructured and sometimes very complex environments, and some form of collaboration with human operators. Incorporating locomotion, sensing, processing, and communications on a single platform is possible, but that platform is by necessity large and expensive and, to be effective, needs to be tailored to a specific mission. The integration of these functions on a small robot is difficult, and progress in all of the technology areas above needs to be developed within the context of specific missions.

Collaboration

The integration of many smaller, less capable robots into a system of distributed robots shows great promise. It has been postulated that many small robots can perform some tasks (not all tasks) more effectively than a single large robot. While simulations of large numbers of robots have demonstrated positive results, this hypothesis has not been proven with real robots in real environments. It is still not clear whether linearly increasing the number of robots performing a single task results in linear, sub-linear, or exponential effectiveness. It is, however, intuitive that for some missions like area searches, multiple collaborating robots assigned to individual sectors (parallel processing) can probably accomplish the task

in much less time than a single robot trying to serially search the area. Effective collaboration requires effective communications among robots and from robots to central processing sites. It also requires novel networking architectures that are adaptable to mission-specific tasks. Finally, efficient algorithms that operate within the architecture need to be tailored to the robot capabilities, the network and the task. Much progress has been made in the collaboration of unattended fixed ground sensors, but using these technical approaches on a large number of mobile sensors offers order-of-magnitude-greater challenges.

Power

Energy requirements for small robots present serious problems. Locomotion, sensing, processing, communications and power all require volume. It is difficult to provide the energy density needed in a small package. There are four main approaches to address the power issue. The first focuses upon the selection of low-power electronics and highly efficient mechanical actuators. The second involves optimizing system performance for specific missions. For example, the processor should not be constantly using clock cycles to interrogate an input/output channel when it is known that no transmission or reception is needed during specific times. The third involves exploring novel energy supply technologies such as using circular watch batteries for wheels, conforming a plastic battery over the surface of the robot, exploiting new energy sources (fuel cells, MEMS generators, etc.), and examining energy scavenging techniques. The fourth level explores the tactical deployment of the robots so they are used in manners that minimize energy consumption.

Small robots can operate continuously for tens of minutes but less than an hour depending upon the various duty cycles associated with locomotion, sensing, processing, and communicating. For highly dynamic missions like hostage rescue and small building takedowns, mission times are short and matched to robot's power needs. For longer duration missions, techniques are required that shut down most of the robot's functions but continue to power a seismic sensor, for example, that can wake the robot into full surveillance operation.

Human-Computer Interfaces

Most robotic operations require interventions by human operators for mission planning and programming, direct teleoperation, providing assistance to robot operations, and interpreting robot sensor information. Human-computer interface (HCI) is typically achieved after the robot

system has been developed. HCI provides an interesting design problem, since human capabilities are fixed at one end and robot interfaces are fixed at the other and the common tools for HCI such as computers, joysticks, or displays are not typically tailored to operations in extreme environments.

Operators typically need to control the robot, interpret the information it is providing, and make decisions in time-critical, dangerous environments. The operator probably has other non-robot functions to perform such as shooting a weapon, communicating to other team members, or serving as a medic. A very sophisticated and capable robot is likely to be completely ignored if the HCI is not simple to use, does not provide intuitive information, or is too heavy or bulky.

Most operator control units consist of a laptop computer with a joystick packaged in a rugged suitcase. This setup requires an operator to place the unit on a level surface, view robot operations either on a sun immersed LCD screen or one that projects light at night, and occasionally enter information via key strokes while wearing protective gloves. Since this in an unacceptable interface, other HCI hardware attempts to match the operator's body though the use of wearable computers and head mounted displays. These solutions still require additional development to reduce their size, bulk and heat signature.

Of significant importance is how information is presented to the operator. Typical computer "window" applications require operator attention to guide and navigate through menus and, thereby, limit the operator's ability to focus on information. Other interfaces provide a display that shows real-time video from a robot camera. This often requires an operator to view the information even when nothing significant is being presented.

There is a strong need for simple-to-use hardware that is environmentally robust, reliable, low power, and unobtrusive. The presentation of information needs to be accomplished in a manner that is intuitive and appeals to the perceptual rather than the cognitive abilities of the operator. New efforts that create and present representations of the environment and objects of interest are needed. Also needed are methods to create representations of representations (meta-representations) to put objects and environments in a mission context.

Many robots are developed with the presumption that their unique design will offer discriminating mobility for a wide variety of users. Developers often become frustrated when military operators inevitably want to add their own sensors and radios resulting in robot modifications that make them larger and able to carry more batteries. A mistaken conclusion is that military operators want large robots. They don't; they

want small, lightweight capability. Robots should not be thought of simply as platforms. They must be designed and developed as a system that provides a capability. The original design must include unique mobility, navigation, communications, processing, autonomy, and human-computer interfaces. The robots must be able to operate with people, other unmanned vehicles, and other sensors within the context of tactics and be able to provide a capability that helps successfully perform a mission.

ANNEX G.

REMOTER FORCE

The U.S. Department of Defense has expanding experience with unmanned platforms. Primarily, this experience has been with unmanned aerial vehicles, which are increasingly an indispensable tool for our warfighters. Indeed, it seems that the challenges of creating significant unmanned capabilities are in the category of present-day urgent needs. While there are important developmental improvements needed in unmanned platform capabilities, a conclusion of this report is that all of the important engineering problems are already being addressed to some degree in the Department's activities with few, if any, obvious ways in which to improve the pace of this work.

There is, however, another opportunity, that would combine the capabilities of current and future unmanned platforms with current and future communications capabilities. What is envisioned is a day when unmanned platforms are remotely operated not from beyond the hill or over the horizon, but from anywhere in the world. Such an approach would have additional collateral benefits, namely, that it might relieve some of the difficult technological challenges that exist today by altering the balance between automation and human remote control. Altering this balance would permit duty cycles that better optimize work and rest cycles since many more individuals would be participating. As well, this approach would relieve some of the detailed control tasks necessary for automated systems by including, at least in the near term, a human in the loop.

Interpretation of information requiring human processing capabilities would be dramatically enhanced. Perhaps most importantly, however, remote operations would change the nature of our views on "military personnel" and allow DoD to effectively use people with extraordinary skills outside the normal circle of uniformed personnel. Indeed, in the limit, active duty personnel might consist not only of uniformed personnel selected for the historically significant war fighting attributes, but also of a *remoter force* selected for their elite capabilities in remote control operations.

An entire "Army" of such "remoters" is in training today. (See Figure G-1.) The revolution in massive multiplayer gaming was discussed in

Chapter III. The idea of a remoter force seeks to extend the concept of this continuous training and concept exploration to a concrete military capability.

Figure G-1. In Training—An Army of Remoters.

This idea amounts to what was referred to in Chapter III as turning the reality dial. MMP is a virtual environment that explores doctrine and behaviors; the Remoter Force is a single realization of the power of such a massively collaborative tool.

The overall objective, therefore, is to include many more people in any conflict in which the Department engages. Not by putting more "boots on the ground," but by force-multiplication: for every one person on the ground, a group of remoters would be responsible for controlling small advanced surveillance systems, processing that data, managing the 24-hour duty cycles required, and performing other support activities. This is the concept behind *Ender's Game*, the science-fiction novel written by Orson Scott Card, which effectively blends the remote world with the physical. This concept would redefine the U.S. fighting force and create a high-fidelity, system-level capability out of massively parallel, low-fidelity pieces that capitalize on the ability to use large, distributed, secure world-wide networks effectively.

For all the revolutionary changes and opportunities that are apparent in this (potentially inevitable) technical concept, it is also one of the most disquieting, particularly for military commanders. In particular, the lack of direct control implied by this concept and the reliance on system-level redundancy over individual element reliability causes great consternation. Among the key questions are the following:

a. How would we determine that the right person is "fighting"?
b. If a 15-year-old has world-class talents in remote control, will he or she have the discipline and emotional maturity necessary to fight in a battle?
c. What are the implications of putting weapons systems on these remote systems at the hands of those not directly on the ground?
d. What are the training implications?
e. What about the limitations of current platforms in terms of endurance, payload, and so on?
f. What is the compromise implied by reducing the fidelity of individual platforms so as to achieve the expendability that would be required to permit non-military personnel to control them?

All of these are problems to be overcome, since they imply new concepts of operations, new procedures, new training, and new enlistment possibilities. These are also cultural and organizational issues, not purely technical ones. Technological requirements also exist, such as the need to ensure security of remote unmanned platform operations with high-bandwidth and near-continuous communications. And we see the implications for training as favorable, especially when combined with the massive multiplayer concepts discussed in Chapter III. Indeed, these capabilities would permit DoD to continuously train and test for the most talented pool of remoters. It should be noted that remoters and "on the ground" forces should train together in order to gain an element of understanding and trust.

As mentioned earlier, the participation of a remoter force is likely to be a future inevitability, especially as wireless, secure communications and high-bandwidth infrastructures improve. Adversaries who do not draw such strong lines of distinction between their fighting personnel and civilians and who are more willing to create distributed command cells will not be so reticent to embrace the power of this collaborative approach. The events of September 11th and the role that personal-computer based

flight simulation, as well as higher fidelity flight simulation, played in preparing the terrorists for their role as hijackers and pilots is but a small premonition of what may be to come.

Technological challenges involving power, sensing, mobility and navigation, among others, are prevalent in the use of unmanned platforms. These challenges are currently addressed in a myriad of DoD programs. (See Annex F for a discussion of ground-platform technology.) These programs are expansive and dedicate large dollars to the overall improvement of such platforms. There appears to be no significant technological breakthrough on the horizon that would significantly alter the pace of improvement, which is largely evolutionary. This observation should not be interpreted as an indictment of current efforts, but rather encouragement to stay the course. The realization of a remoter force will perhaps ease some of the demand by focusing on a largely underdeveloped aspect of the use of such platforms: namely, achieving the desired goals through massive parallelism and the direct intervention of humans on a large scale.

ANNEX H.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ACTD	Advanced Concept Technology Demonstrations
AEF	Air Expeditionary Force
BDA	Battle Damage Assessment
BW	Biological Warfare
C4ISR	Command, Control, Communications, and Computers and Intelligence, Surveillance, and Reconnaissance
C4I	Command, Control, Communications, Computers and Intelligence
CEO	Chief Executive Officer
CINC	Commander-in-Chief
CJCS	Chairman, Joint Chiefs of Staff
CONUS	Continental United States
CTO	Chief Technology Officer
DARPA	Defense Advanced Research Project Agency
DDR&E	Director, Defense Research and Engineering
DOT&E	Director, Operational Test and Evaluation
DSB	Defense Science Board
DTED	Digital Terrain and Elevation Data
DTRA	Defense Threat Reduction Agency
EMD	Engineering and Manufacturing Development
EMW	Expeditionary Maneuver Warfare
FCS	Future Combat System
FDA	Food and Drug Administration
GMTI	Ground Moving Target Indicator
GPS	Global Positioning System
HCI	Human-Computer Interface

HHS	Health and Human Services
ISR	Intelligence, Surveillance and Reconnaissance
JFCOM	Joint Forces Command
MEMS	Micro-Electro-Mechanical System
MMP	Massive Multiplayer
NCO	Network Centric Operations
NIH	National Institutes of Health
OSD(C3I)	Office of the Secretary of Defense for Command, Control, Communications and Intelligence
PPBS	Planning, Programming and Budgeting System
R&D	Research and Development
RAP	Rapid Acquisition Program
RDT&E	Research, Development, Test and Evaluation
RF	Radio Frequency
S&E	Scientists and Engineers
S&T	Science and Technology
TEG	Thermo-electric
TRAC	Threat Reduction Advisory Committee
UAV	Unmanned Aerial Vehicle
UHF	Ultra High Frequency
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology and Logistics
VC	Venture Capital